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SYSTEMS ENGINEERING CAPSTONE PROJECT REPORT

A SYSTEMS APPROACH TO FINDING COST-EFFECTIVE ALTERNATIVES TO EUROPEAN BALLISTIC MISSILE DEFENSE

by

Cohort 311-114O

September 2013

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TO THE EUROPEAN BALLISTIC MISSILE DEFENSE**

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ABSTRACT

Increasing political tensions between nations, coupled with advancements in technology, have resulted in the need for a Ballistic Missile Defense (BMD) system, specifically in the European theater where ally nations are particularly vulnerable. This report focuses on defending Turkey with a solution that could be fielded by FY18. It includes the following mature technologies: Patriot Advanced Capability-3, Terminal High Altitude Area Defense (THAAD), Army Navy/Transportable Radar Surveillance (AN/TPY-2), and BMD capable Aegis ships. Compiling the anticipated needs of stakeholders and identifying the most prominent threat focuses the research efforts. To identify any functional gaps the analysis uses functional decomposition and flow block diagrams before entering modeling and simulation. By focusing on footprint area defense and testing multiple scenarios, performance gaps are revealed; generic parameters keep this report unclassified. The results from the simulations led to several alternatives. Alternative A places two BMD Aegis capable ships along the northern and southern coasts of Turkey; Alternative B specifies several THAAD batteries in various locations; and Alternative C dictates an Aegis Ashore in the eastern region of the country. Alternative C was determined to be the best choice, taking into account modeled performance and total life-cycle cost.

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LIST OF ACRONYMS AND ABBREVIATIONS

1VM	One Versus Many
2D	Two Dimensional
3D	Three Dimensional
AAMDC	Army Air And Missile Defense Command
ACCS	Air Command And Control System
AGI	Analytical Graphics Incorporated
AN/TPY-2	Army Navy Transportable Radar Surveillance Model 2
API	Ascent Phase Intercept
BCN	Battle Command Network
BMD	Ballistic Missile Defense
BMDR	Ballistic Missile Defense Review
BSRBM	Battlefield Short Range Ballistic Missile
C2	Command And Control
C2BMC	Command, Control, Battle Management and Communication
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance
CNSSP-15	Committee on National Security Systems Policy
COS	Community of Systems
DAF	Defended Area Footprint
DoD	Department of Defense
EBMD	European Ballistic Missile Defense
EFFBD	Enhanced Functional Flow Block Diagram
EM	Evaluation Measures
EPAA	European Phased Adaptive Approach
EU	European Union
EUCOM	European Command
FBR	Forward Based Radar
FDR	Forward Deployable Radar
GAO	Government Accountability Office
GOTS	Government Off The Shelf
HEL-MD	High Energy Laser Mobile Demonstrator
ICBM	Intercontinental Ballistic Missile
IDEF0	Integration Definition For Function Modeling
IFT	Interceptor Flight Tool
IMD	Integrated Missile Defense
IR	Infra-Red
IRBM	Intermediate Range Ballistic Missile
IWS	Integrated Warfare Systems
JFCC	Joint Functional Component Command
JLENS	Joint Land Attack Cruise Missile Defense Elevated Netted Sensor System

KEI	Kinetic Energy Interceptor
LCC	Life Cycle Cost
M&S	Modeling And Simulation
MCT	Missile Conversion Tool
MDA	Missile Defense Agency
MDT	Missile Design Tool
MMT	Missile Modeling Tool
MRBM	Medium Range Ballistic Missile
MTBF	Mean Time Between Failure
MTTR	Mean Time To Repair
NATO	North Atlantic Treaty Organization
NAVSEA	Naval Sea Systems Command
O&S	Operation And Support
OSD	Office Of The Secretary Of Defense
OUSD-ATL	Office Of the Under Secretary of Defense for Acquisition, Technology, and Logistics
P&C	Production And Construction
PAC-3	Patriot Advanced Capability 3
PEO	Program Executive Office
P_{fd}	Probability Of Footprint Defended
P_i	Probability Of Intercept
PTSS	Precision Tracking Space System
R&D	Research And Development
SAIC	Science Applications International Corporation
SBX	Sea-Based X-Band Radar
SECDEF	Secretary Of Defense
SLV	Space Launch Vehicle
SM-3	Standard Missile 3
SOS	System Of Systems
SRBM	Short Range Ballistic Missile
SRBOC	Super Rapid Bloom Offboard Countermeasures Chaff
STK	System Toolkit
STRATCOM	Strategic Command
STSS	Space Tracking & Surveillance System
TECHREP	Technical Representative
THAAD	Terminal High Altitude Area Defense
TTP	Tactics, Techniques and Procedures
UAV	Unmanned Aerial Vehicle
UEWR	Upgraded Early Warning Radar
U.S.	United States
USD-P	Under Secretary of Defense for Policy

EXECUTIVE SUMMARY

The proliferation of ballistic missile threats to the United States and its allies garners much attention in the Department of Defense. Ballistic missiles have become more accessible to hostile nations and more capable in recent years as missile technologies have matured. This problem is particularly worrisome for United States allies in Southern Europe, who must contend with ballistic missile threats from Iran. While the United States is actively countering such threats with rapidly maturing ballistic missile defense technologies, the problems are changing as fast as the solutions. The current threats are evolving with geographic and political alliances, advancing technical solutions, and the high costs of the solution components. The currently envisioned approach to defend Southern Europe against ballistic missile threats cannot adapt to evolving threats, does not address rapid advances in technology, nor does it provide an affordable solution.

To understand the problem of ballistic missile defense in southern Europe, various stakeholders were determined and organized by type (resource stakeholders, policy stakeholders, operation stakeholders and acquisition stakeholders). Stakeholder needs were identified to construct a set of common needs and priorities that any solution must meet. From stakeholder analysis, it was identified that a system was needed that was cost effective, straightforward to procure, and available in the very near future.

The ballistic missile threat and defense problem spaces were examined to acquire necessary information with respect to existing technologies and concepts that any solution must be cognizant of. In addition, the physical constraints specific to the field of ballistic missiles were examined.

With the needs and constraints identified, the cohort formalized them into a set of requirements (such as "The EBMD system shall have a 97% probability of detection at a 95% confidence level" and "The EBMD system shall be able to engage up to five ballistic missiles at a time") that could be used to construct solution agnostic functional architectures and evaluate them. The requirements were categorized into functional and non-functional types and evaluation measures were defined to provide performance and

cost targets that any solution could be compared against. Those evaluation measures included the ability of a system to defend the geographical footprint of Turkey, the probability of a system to successfully intercept a ballistic missile threat originating from Iran, and life cycle costs of a system over a 10-year period.

Functional analysis was then performed to understand how any solution would need to operate in order to meet the needs of the stakeholders and to understand fully the hierarchical and architectural details that any solution must provide. Through the construction of functional hierarchies as well as functional flows, the critical system behaviors and priorities were identified and used to determine how a suitable solution should behave.

Those critical system behaviors were then allocated into a series of alternative architectural definitions that were directly traceable to requirements and could be used when conducting simulations to further refine, understand and functionally validate how a solution may perform. Those architectures were varied combinations of BMD components (Aegis ships, Aegis Ashore, THAAD interceptors, PAC-3 interceptors, and the AN/TPY-2 radar system) in an operational or near-operational state, as well as a Baseline architecture that functionally represented what is currently used to defend against ballistic missile threats in Southern Europe.

The Baseline and EBMD Alternative architectures were entered into a software suite of missile modeling tools called Systems Toolkit by AGI, Inc. Those tools simulated their performance using two evaluation methods.

The first method, called "One Versus Many," evaluated the ability of the various architectures to defend against specific incoming ballistic missile threats with a known target. In this simulation, it was clear that battle delay and target locations play a critical role in the ability of an alternative architecture to successfully intercept a ballistic missile threat. This insight shows that architectures where the interceptors are located closest to the threat are more effective.

The second method, called "Defended Area Footprint," evaluated the ability of the alternative architectures to defend a defined geographic area (for this project, the

borders of Turkey). This simulation demonstrated that having multiple interceptor systems covering the same geographic area significantly increases the probability of an area being defended.

With the help of the software simulation tools, the cohort was able to further refine and evaluate the performance characteristics of various solution architectures (called Alternatives A, B.1, B.2, B.3 and C).

The EBMD Alternative that performed best (highest Percent Footprint Defended and highest Probability of Intercept), labeled B.3, had two Aegis ships and three Terminal High Altitude Area Defense (THAAD) BMD interceptor batteries (the most THAADs of any alternative architecture).

The life cycle costs over a 10-year period were then calculated for each EBMD Alternative. Using cost data from the MDA Fiscal Year 2013 Budget, component costs were identified for each BMD component in the alternative architectures, and their combined costs were calculated. These calculations showed that each EBMD Alternative was cheaper than the Baseline architecture. The highest cost drivers were production and construction and quantity of interceptors held by the system. The alternative architecture utilizing Aegis Ashore (Alternative C) was the least expensive alternative due to its reuse of technologies developed for Aegis ships.

Equipped with performance and cost data for each EBMD Alternative, the alternative architectures were evaluated. It was determined that Alternative C provided the best balance between cost and performance.

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I. INTRODUCTION

A. BACKGROUND

Thirty-one countries currently possess operational ballistic missile systems with ranges varying from 120 km to 15,000 km (Arms Control Association 2012). At least three of these countries, Iran, North Korea, and Syria, are deemed overtly hostile to the United States (U.S.) or nations in the North Atlantic Treaty Alliance (NATO). Several other countries could reasonably become hostile in the next decade (Missile Defense Agency 2012c).

Iran, North Korea, and Syria are capable of inflicting serious damage to the U.S. or its allies. To protect against ballistic missile threats, the U.S. and NATO have invested in a complex, global missile defense system. This defense system is overseen by the U.S. Department of Defense (DoD) Missile Defense Agency (MDA) and is termed the Ballistic Missile Defense (BMD) System.

The BMD system employs regional and global networks of sensors that can detect missile launches or incoming threats and alert active-defense systems to neutralize the threats. BMD also employs defensive missile interceptor batteries afloat and ashore, as well as ground and airborne weapons systems that work to detect and destroy the threats.

A large number of sensors and defense systems must be placed throughout the world to assess and neutralize incoming ballistic missile threats in near real-time. To address these threats to Europe and the Eastern U.S. seaboard, the U.S., in partnership with other NATO allies, is currently developing and deploying missile defense systems throughout Europe, identified throughout this report as European Ballistic Missile Defense (EBMD).

The problems surrounding the EBMD domain are large and dynamic. The issue spans a long list of factors, all of which contribute significantly to the EBMD problem. Those factors include:

Geographic and Political Alliances

Sources of funding and policies are often organized by regions or countries. EBMD solutions encompass many of these organizations, whose priorities widely vary.

Technical Solutions and Components

EBMD encompasses a wide variety of weapons systems, sensors, networks, and supporting organizations. None of these systems can operate effectively in a vacuum, and varying capabilities and costs serve to create a patchwork of related systems and capabilities.

Technical Maturity Levels

EBMD components are constantly developing and improving. Deployed EBMD systems must coexist with similar but enhanced versions being deployed elsewhere. These enhancements complicate capability assessments when studying EBMD components as a whole system of systems (SoS).

A Solution Trade Space with Numerous Degrees of Freedom

The threat is equally as dynamic as the solution, and this contributes a number of factors that must be analyzed in the solution space including locations, threat and interceptor capabilities, costs, weapon program maturities and conflicting stakeholder needs. The most effective tradeoffs and compromises vary as widely as the EBMD environment.

1.   Emerging Common Themes

Careful evaluation of the issues in the EBMD domain eventually started to suggest three common themes that could be addressed from a systems engineering perspective. These problems were consistent, spanned many sources, and required solutions that could be reached using the tools and techniques available to a systems engineer.

The key problems facing EBMD are evolving threats, changing technology, and budget constraints.

a.   Evolving Threats

The threats to U.S. allied entities within Europe are changing at a fast pace. The threats span numerous aggressor countries with varied advancement of technologies. While solutions try keep pace, they often leapfrog and then fall behind new threat developments. The Iranian threat in particular shows a continued advancement that must be matched with maturing short and medium range EBMD solutions.

As Cappaccio (Cappacio 2012) explains, Iran has been improving its accuracy with respect to missiles. Cappaccio cites a Congressional Research Service analyst, Kenneth Katzman, who observed of a report discussing an assessment of Iran's military power:

> There was a theme that Iran is improving the accuracy and lethality of its missiles […] U. S. government reports have previously always downplayed the accuracy and effectiveness of Iran's missile forces. […] The report seemed pretty sober and respectful of Iran's capabilities, crediting Iran with improving survivability. (Katzman, quoted in Cappacio 2012, para. 7–8).

The current methods of addressing ballistic missile threats have significant lead times. Those lead times are often dependent on varying political, technical and developmental constraints. Such constraints serve to hamper the abilities to address EBMD threats. Those threats in turn, are often given the opportunity to advance faster than the solutions. Effective containment of ballistic missile threats requires a solution that can answer to an adaptable and dynamic threat environment.

b.   Changing Technology

EBMD technology is developing at a significant pace from both sides of the problem. The MDA releases news on a regular basis (Missile Defense Agency 2013e) capturing the aggressive and expensive pace of BMD system solutions development (as seen in Figure 1). Several interceptor tests have also occurred since the European Phased Adaptive Approach (EPAA) was announced in 2009.

Phase I: Today's Capability	Phase II: Enhanced Medium-Range Missile Defense (By 2015)		Phase III: Enhanced Intermediate-Range Missile Defense (By 2018)		Phase IV: Early Intercept of IRBMs and Potential ICBMs (By 2020)	
Aegis BMD 3.6.1 with SM-3 IA — SM-3 IA	Aegis BMD 4.0.1/5.0 with SM-3 IA/IB — SM-3 IB	Aegis Ashore 5.0 with SM-3 IB (Romania)	Aegis BMD 5.1 with SM-3 IA/IB/IIA — SM-3 IIA	Aegis Ashore 5.1 with SM-3 IB/IIA (Poland and Romania)	Aegis BMD 5.1x with SM-3 IA/IB/IIA — SM-3 IIB	Aegis Ashore 5.1x with SM-3 IB/IIA/IIB (two sites)
AN/TPY-2 (FBM)	AN/TPY-2 (FBM)		AN/TPY-2 (FBM)		AN/TPY-2 (FBM)	
C2BMC AOC Ramstein — ALTBMD Interim Capability	C2BMC Updates — ALTBMD Lower Tier	Potential EPAA Surge — THAAD	C2BMC Updates — ALTBMD Upper Tier	Potential EPAA Surge — THAAD Launch on Remote	Enhanced C2BMC	Potential EPAA Surge — THAAD Full Network

Figure 1.   MDA Development Goals for BMD System Solutions in Europe (From Missile Defense Agency 2012a)

While the current EBMD solutions are by no means static, they often occur as standalone solutions and do not holistically address the developmental pace of the constituent components. EPAA in particular, which is the presidentially-directed policy for missile defense in Europe, has been criticized by the Government Accountability Office (GAO) for its decision to view various missile defense capabilities as "tool kits" for the regional commands, and for not requiring an integrated missile defense architecture but instead relying on proven solutions (GAO 2010). In December 2010, the GAO noted:

> DoD has not yet determined the full set of BMDS system elements that will participate in EPAA [….] Although DoD has begun to plan and implement EPAA, it has not yet established architectures with systems and quantities for the phases [….] DoD's decisions to manufacture, produce, and field missile defense systems are outpacing testing, modeling, and validation, resulting in decisions being made with limited understanding of system effectiveness.[…] As efforts to meet near-term commitments unfold, the schedule for delivering capabilities may be difficult to achieve and resources needed may grow. (GAO 2010, 13–24)

The pace of changing technology must be addressed more effectively in any overarching EBMD solution.

c.   Budget Constraints

In January 2011, the GAO made it abundantly clear to the DoD that life cycle costs estimates and cost containment are not being earnestly addressed for dollars spent on EBMD.

> Although DoD reported that the acquisition cost estimates and annual BMD budget request for individual elements include EPAA costs, we found that such information does not include full life cycle costs. Further, this budgeting method is fragmented and so does not provide decision makers with a transparent and holistic view of EPAA. (GAO 2011, 13)

This makes it difficult for decision makers to determine if the current approach is affordable or properly funded.

2.   The Problem

The currently envisioned approach to defend Europe against ballistic missile threats cannot adapt to evolving threats, does not address rapid advances in technology, nor does it provide an affordable solution.

B.   RESEARCH QUESTIONS

The cohort evaluated the EBMD problem from the perspective of cost control, technical flexibility, and effective use of existing component capabilities. The solution needed to be able to contain the immediate threat to Europe posed by Iran and do it with those central issues as the top priority. During that evaluation, the following research questions were explored:

1.   What Are the Primary Regional Threats?

The DoD has acknowledged that technological advances in materials, propulsion, warheads, and sensors have resulted in ballistic missile systems that "are becoming more flexible, mobile, survivable, reliable, and accurate, while also increasing in range"

(Secretary of Defense 2010). How do we quantify those changes? What other potential adversaries could evolve?

2. What Are the Needs of the Stakeholders?

How do NATO, our European allies, and DoD stakeholders expect an EBMD solution to best serve their priorities? How can we ensure that the stakeholders remain free of a ballistic missile threat?

3. What Are the Existing Solutions?

The MDA is currently operating an EBMD system that will protect NATO, our European allies, and our interests. There are assertions that the current system has holes in its ability to cover the entire region as required. What are the existing approaches to ballistic missile defense in Europe?

4. What Are the Existing System Limitations?

There are many limitations to countering the ballistic missile threats. The GAO indicates that performance gaps in the European ballistic umbrella have not been fully quantified or understood.

> The system's desired performance is not yet defined using operationally relevant quantifiable metrics, such as how long and how well it can defend. The combatant commands are attempting to define operational performance metrics to enable credible assessment of operational performance gaps. However, these metrics have yet to be finalized and implemented. Without a more complete understanding of BMD operational capabilities and limitations, the combatant commands face potential risk in EPAA operational planning. (GAO 2011, 2)

How can these limitations be quantified and how can those quantifications be leveraged to ensure an effective solution?

5. What Viable Solutions Can Be Formulated?

Currently, one solution being sought by the DoD is the increased production and procurement of proven technologies such as THAAD, the Standard Missile 3 (SM-3) interceptor, and the AN/TPY-2 radar (Secretary of Defense 2010). This solution has

become increasingly more difficult to realize due to DoD fiscal constraints. What are the most effective methods of defending Europe against a ballistic missile threat?

C.   ASSUMPTIONS

The issues surrounding EBMD are sensitive (both technical and political). All research and analysis for this project was unclassified, and based on publically available information. Without privileged access or knowledge of more protected information sources, it was assumed that the information from trusted and reputable unclassified public sources was accurate, factual and current. The insights formulated by the cohort were dependent on such assumptions and may not suggest a solution that reflects the insights that would be available with access to classified information. However, the process to reach such conclusions drawn in this paper is valid based on the sources the cohort did have available to them, and can be leveraged against more protected sources to aid in solving the problem at hand.

D.   SYSTEMS ENGINEERING PROCESS

The cohort focused on the processes from stakeholder needs through alternatives analysis presented in the classic Vee model (Blanchard 2011, 34), and did not create any components or products that would be testable or deployable. A more detailed description of the decomposition and definition side of the Vee was created and the integration and verification sequence was removed. This new tailored systems engineering process also had a few adaptations to better use the available analysis personnel in the cohort.

The systems engineering process (Figure 2) divided the cohort into functional groups that were responsible for owning the various sub processes and contributions to the report. Those major sub processes included:

The problem space exploration process, whose functional group explored the needs of the stakeholders, understood the mission and missile concepts, and identified the threats and existing BMD components to be used in formulating a quantifiable problem.

The requirements analysis process, whose functional group compiled the BMD needs specific to the project problem and converted them into a set of Functional

Requirements, Non-Functional Requirements and Evaluation Measures (EM) that could be used for detailed functional analysis and identifying alternatives.

The functional analysis process, whose functional group decomposed the problem space into a functional hierarchy and defined the functions and flows of missile defense into a system definition that could be traced to requirements.

The alternatives generation process converted the functional architecture generated during functional analysis into a set of initial alternative architectures that could be modeled and simulated to identify performance trends and architecture behaviors.

The modeling and simulation (M&S) process, whose functional group took the initial alternative architectures and converted them into system models that could be evaluated and explored. Those models were tested in simulation software to validate their ability to meet the needs of the stakeholders.

The alternatives refinement process, whose functional group took the insights gained during M&S and used them to create a new set refined alternatives that better met the needs of the stakeholders than the initial alternative architectures.

The life cycle cost analysis process, whose functional group identified the costs of the alternatives. Those costs were used to evaluate and compare the alternatives and identify the ones that were the most economical.

The alternatives analysis process, whose functional group combined the performance results of the refined alternatives learned during M&S, the Evaluation Measures created by the requirements analysis process, and the life cycle costs to recommend an EBMD system architecture that is affordable and effective.

A program and document management process was also introduced, whose functional group centrally directed all the other functional groups as well as managed the project. This functional group was responsible for leading and organizing meetings, steering the project towards its goals, and managing the final report and presentation deliverables.
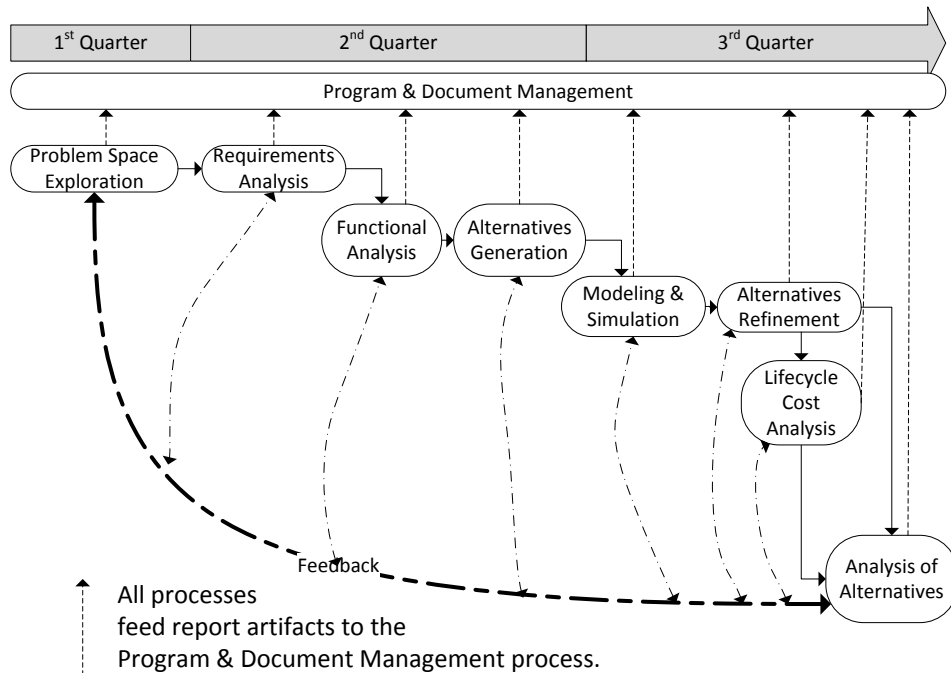
Figure 2.   Tailored SE Process Model (After Blanchard 2011, 34)

Classic Vee models assume that the initial processes are static and can be addressed serially. However, it was anticipated this project would require revisiting and revising artifacts based on uncovering information and learning more about the problem at hand, so explicitly including feedback loops between all processes was necessary. Processes are described in detail in subsequent chapters of the report.

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II. PROBLEM SPACE EXPLORATION

A. PROBLEM SPACE EXPLORATION PROCESS

Before formalized requirements could be created, the cohort needed to fully understand exactly what the problem was, and how that problem needed to be addressed. The problem space exploration process needed to explore the factors that drive BMD solutions, and catalog them in a manner that could be readily and easily interpreted during requirements analysis.

Problem space exploration (Figure 3) was divided into two efforts. Stakeholder analysis was used to identify the needs and wants of organizations that deal with BMD issues. The mission needs analysis was used to fully understand the BMD concepts and components that would constrain the architecture of our system, including the physical aspects of how BMD works, the actual threats to BMD and the existing components and systems environment that our solution needed to work with. The results of the problem space exploration process drove the requirement analysis, and helped inform the cohort of architectural and functional factors that impacted the EBMD solution.
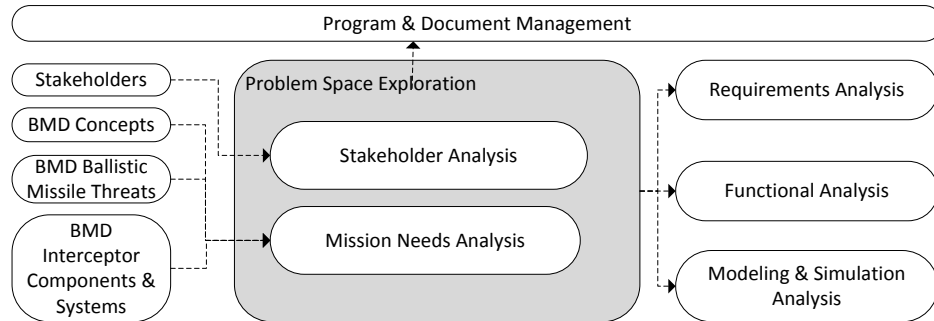
Figure 3.   Problem Space Exploration Process

B. STAKEHOLDER ANALYSIS

Many parties have a stake or interest in EBMD. Their roles range from research and design to military organizations implementing the solutions. Conversely, other states and organizations posing a threat to European security have an interest in overwhelming

or subverting the capabilities of any EBMD system. These parties, largely from the Middle East, pose a capable and serious threat, and create the need for a comprehensive EBMD system. A detailed analysis was conducted to understand these stakeholders.

1. Stakeholder Analysis Process

Obtaining information from the EBMD stakeholders, including priorities and requirements, is key to engineering a successful system. To obtain that information, the cohort created and followed the stakeholder analysis process shown in Figure 4. The cohort identified stakeholders by researching publically available government documentation to understand the varying needs and issues related to EBMD. After the stakeholders were identified, the cohort separated the stakeholders into Resource, Policy, Operations and Acquisition categories.

The cohort originally intended to collect detailed information on these stakeholders and their needs through various research avenues and by soliciting specific stakeholders with specific questions. Despite repeated attempts however, the cohort was unable to obtain any individual responses from those contacted. Subsequent research was solely conducted using openly available government produced reports and third party websites. This research was then analyzed to infer stakeholder needs.

The analysis began with the organization of stakeholder types. It continued with the research phase which was intended to complement direct feedback from stakeholders, but eventually served as the sole source to understand stakeholder priorities, requirements, and other needs. Without input from actual stakeholders, the cohort used the questions as guidance to further research and the cohort's interpretation of the problem. Once detailed stakeholder information was compiled, the cohort analyzed the sources and inferred the requirements necessary for any successful EBMD solutions.
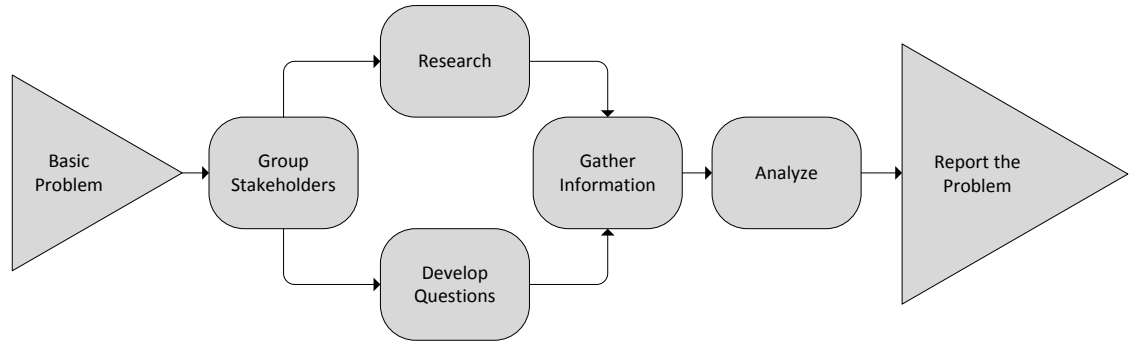
Figure 4.   Understanding the Stakeholders

2.   Stakeholder Details

The organizations that have a stake or interest in the EBMD systems, as well as what we learned about them and what they want from the systems, were then organized (Research Question 2).

a.   *Resource Stakeholders*

Resource stakeholders provide the necessary resources to develop, deploy, and operate an EBMD system. They are responsible for evaluating competing programs against warfighter needs and providing the actual budget and schedule expectations to acquisition entities.

(1)   Missile Defense Agency. The MDA is the key decision maker in U.S.-affiliated EBMD arenas. This role is defined by their mission to develop, test, and field an integrated, layered, EBMD system to defend the U.S., its deployed forces, allies, and friends against all ranges of enemy ballistic missile threats in all phases of flight. In addition, they test and evaluate alternatives for the BMD systems.

The defense of Europe is complicated by the fact that it requires the MDA to manage an acknowledged system-of-systems (SoS) architecture (Office of the Director, Defense Research and Engineering, DoD 2010). This SoS architecture combines the individual capabilities of ships, radar systems, ground missile batteries, and other command and control (C2) systems. Because these various systems are owned and operated by different commands and services, the MDA works closely with the various

DoD parties and those not managed by the U.S. For example, the MDA is presently working with U.S. allies to integrate U.S. EBMD technology with NATO members' missile defense capabilities and NATO's C2 systems. The MDA will continue to work with NATO to plan and deploy elements in Northern and Southern Europe as well as consult on specific deployment options and the overarching EBMD system architecture (White House Office of the Press Secretary 2009). This multi-national integration is vital to the successful operation of EBMD systems. Failure by the MDA to use the geopolitical environment to guide system constraints on the EBMD solution will likely result in the failing to defend Europe.

As a guideline, Lt. Gen. O'Reilly of the MDA states that the missile defenses need to "be adaptable (mobile or transportable, able to rapidly expand deployed interceptor inventories and readily upgradable)" (O'Reilly 2011, 3). Furthermore, the system's capabilities must be economically sustainable over the long term (Missile Defense Agency 2011).

The MDA also lists several objectives to develop a system that will assist with the defense of Europe. The system must defend the U.S. homeland against long-range ballistic missile threats. It must speed the protection of U.S. deployed forces, civilian personnel, and their accompanying families against a near term European threat. Additionally, the system must ensure and enhance protection of the territory and population of NATO allies per presidential directives, and do so by deploying proven capabilities and technologies that meet the current threats while providing flexibility to upgrade and enhance the architecture (Missile Defense Agency 2012c).

b.   *Policy Stakeholders*

Policy stakeholders develop DoD policy and doctrine to be followed for the acquisition and operation of missile defense systems. These organizations may or may not have a direct stake in the system at hand.

(1)   Office of the Secretary of Defense. The Office of the Secretary of Defense (OSD) sponsors the MDA and the U.S. EBMD system effort. The OSD and several offices underneath have each made statements regarding their understanding and goals of defending Europe. For instance, the Secretary of Defense (SECDEF) stated that the system needs to be able to negate every deployable missile in an enemy's inventory (Secretary of Defense 2010, 27). The SECDEF added that these capabilities "must undergo testing that enables assessment under realistic operational conditions" (Secretary of Defense 2010, iii).

The Under Secretary of Defense for Policy (USD-P) develops and integrates U.S. missile defense policy within the broader framework of national security strategy and ensures consistency between missile defense policy, development and acquisition plans, and approaches (Deputy Secretary of Defense 2009, 7). The USD-P is also responsible for the coordination of the Ballistic Missile Defense Review (BMDR) (Office of the Under Secretary of Defense for Policy 2012).

The Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics (OUSD-AT&L) provides acquisition policy direction, program guidelines, and overall management oversight of the MDA as chair of the Missile Defense Executive (Deputy Secretary of Defense 2009, 2). Additionally, the USD-ATL makes recommendations to the Deputy Secretary of Defense on missile defense issues. As the manager of MDA, OUSD-AT&L must oversee acquisitions, including procurement of goods and services, research and development, developmental testing, and contract administration for all elements of the MDA.

According to the USD-P, the Joint Staff, and the MDA, regional combatant commands are responsible for translating policies to defend Europe into specific requirements to allow military forces to execute the policy (GAO 2011, 10). The primary geographic command planning and implementing the defense of Europe is the U.S. European Command (United States European Command 2012b).

(2)   Office of the Secretary of State. The Secretary of State is responsible for international relations. The Secretary negotiates and interprets international treaties including membership in NATO. BMD not only affects

relationships with NATO allies, but also those with nations and alliances such as Russia and the Russian Federation. The U.S. is constantly considering the strategic stability between the U.S, NATO, the European Union (EU), and Russia. As already seen through delicate U.S. – Russia discussions on placement of missile defense equipment, BMD has a profound impact on international relationships.

c. Operations Stakeholders

Operations stakeholders are the operational users of the system. These stakeholders directly interact with the system and can provide valuable feedback regarding EBMD system design and functionalities.

(1) U.S. European Command. USEUCOM is a geographic combatant command whose area of responsibility includes all of Europe (including Russia and Turkey), Greenland, Israel, and surrounding waters. It assists in the defense of Europe through efforts by its service components, principally U.S. Naval Forces Europe, U.S. Army Europe, and U.S. Air Forces Europe. The USEUCOM mission is to conduct military operations, international military engagement, and interagency partnering to enhance transatlantic security and defend the U.S. forward (United States European Command 2012a). With regards to missile defense, EUCOM's objective is to "advance NATO European ballistic missile defense through an integrated approach built on balanced contributions" (United States European Command 2012b).

According to the USEUCOM 2012 Posture Statement, the Navy has deployed two Aegis ships already to the European theater. These versatile, multi-mission platforms will perform EBMD functions, but also a myriad of other tasks including maritime security operations, humanitarian missions, and bilateral and multilateral exercises. Meanwhile, the U.S. Air Forces in Europe also must share their resources between providing C2 for U.S. EBMD forces, coordinating with NATO Air Command, and their traditional non-EBMD duties across the continent (United States European Command 2012b).

As the regional command operating and maintaining the EBMD system, as well as the responsible party for protecting U.S. assets in the area, USEUCOM

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must ensure the EBMD system meets their requirements. They must ensure they can procure the system in sufficient quantities and in a timely manner, and that the system performs as expected.

(2)   U.S. Strategic Command. The U.S. Strategic Command (STRATCOM) is a functional combatant command that must integrate global missions and capabilities across the geographic combatant commands. Such duties include planning, integrating, and coordinating global missile defense, including missile dense advocacy for the combatant commands. According to their mission statement, "STRATCOM conducts global operations in coordination with other Combatant Commands, Services, and appropriate U.S. Government agencies to deter and detect strategic attacks against the U.S. and its allies, and is prepared to defend the nation as directed" (United States Strategic Command 2011).

The STRATCOM provides unique requirements that pertain to long-range or global threats and must ensure that these requirements are met in order to protect the U.S. mainland and assets threatened by ballistic missiles not covered by USEUCOM.

(3)   Army Air and Missile Defense Command. The Army Air and Missile Defense Command (AAMDC) conducts joint and multinational operations and planning in support of BMD and provides mission command for Army air defense units. The 10th AAMDC operates the AN/TPY-2 radar and PAC-3 in the European theater. The 32nd AAMDC currently operates the THAAD system and is based in Fort Bliss, Texas.

(4)   Joint Functional Component Command for Integrated Missile Defense. The Joint Functional Component Command for Integrated Missile Defense (JFCC IMD) recommends the global allocation of low-density, high-demand assets, including force rotations, and force sufficiency. The JFCC IMD is burdened with making the best use of limited resources (Senate Committee on Armed Services 2012). This task also increases interoperability with existing C2 systems. The JFCC IMD ensures that the EBMD system is operable and supportable by the various multinational organizations involved.

d.   *Acquisition Stakeholders*

Acquisition stakeholders use available resources to procure the needed systems. The acquisition process usually involves a wide range of personnel ranging from systems engineering to resource managers. Not all the organizations in this stakeholder grouping interact directly with the system, but they are crucial to EBMD execution and life cycle decisions.

(1)   Program Executive Office for Integrated Warfare Systems. The Program Executive Office for Integrated Warfare Systems (PEO-IWS) manages surface ship and submarine combat technologies and systems. They also coordinate the Navy Open Architecture across ship platforms. The PEO-IWS is responsible for acquiring, developing, delivering and sustaining integrated weapons systems for ships, submarines, carriers and aircraft with 155 programs and a $5.8 billion annual budget (NAVSEA 2012a). PEO-IWS is also responsible for managing the development and procurement of the Standard Missiles (SM) and Aegis ships which are available for rapid deployment to protect European nations from Iranian ballistic missile threats.

(2)   Aegis Technical Representative. The Aegis Technical Representative (TECHREP) is a shore activity of the Naval Sea Systems Command (NAVSEA). They report to the PEO IWS. The Aegis TECHREP provides on-site technical oversight of the Aegis system contractor and contributes to all phases of combat system research, development, production, acceptance, delivery, modernization and in-service support. The Aegis TECHREP exercises decision authority trade-offs affecting performance, cost, schedule, design, and reliability (NAVSEA 2012a, 20).

(3)   Program Executive Office – Ships. The Program Executive Office – Ships (PEO-Ships) manages acquisitions for all current and future non-nuclear U.S. Navy surface ships. As one of the Defense Department's largest acquisition organizations, the PEO-Ships is responsible for managing the development and procurement of a diverse array of major shipbuilding programs ranging from complex warships (such as frontline surface combatants and amphibious assault ships), to special mission and support ships (such as air-cushioned landing craft, oceanographic research

ships and special warfare craft). The PEO-Ships is committed to delivering affordable ships to the U.S. Navy fleet (NAVSEA 2012b).

PEO-Ships manages the development and construction of 10 major ship classes and a wide range of small boats and craft. Three of these classes (CG-47, DDG-51 and DD-1000) are Aegis-equipped ships that compose part of the existing EBMD. These Aegis-equipped ship classes are key components to EBMD.

As acquisition-related stakeholders, PEO-IWS, Aegis TECHREP, and PEO-Ships all strive to maximize fleet commonality and current fleet inventory. They manage modifications to existing systems through disciplined policies, processes and procurements. They also aim to use established contract vehicles to achieve their goals whenever possible. These goals place aggressive cost and efficiency constraints on the EBMD solution.

C.   MISSION NEED ANALYSIS

In a speech made by U.S. president Barack Obama on 17 Sep, 2009, regarding strengthening missile defense in Europe, the president called for a new missile defense architecture in Europe that would provide stronger, smarter and swifter defense of American forces and America's allies (Postol 2009). Shortly after the presidential speech, NATO leaders of the 2010 Lisbon Summit adopted a strategic concept that committed NATO to meeting the security challenges of the 21st century. These challenges ranged from terrorism to ballistic missile and cyber-attacks to nuclear proliferation (White House 2012). NATO leaders also decided to expand the Theatre Missile Defense Program to include the protection of NATO European populations and territories.

In response to these security concerns, the cohort conducted a mission need analysis for this report, to identify possible capability needs for a ballistic missile defense system, with the primary mission being to protect U.S. forces, allies, and other countries within the European region from ballistic missile threats.

1. Threat

The primary missile threat to European NATO countries is based on regionally-launched ballistic missiles. A limited number of threat nations have such capabilities.

Iran specifically maintains operational ballistic missile weapon systems capable of short and medium range distances, with the potential to develop intermediate range capabilities in the near future (Missile Defense Agency 2013d). Due to its proximity to Turkey, all of these weapons are a threat. The addition of the 'Sejil' missile class gives Iran the ability to strike not only the entire country of Turkey, but also other European nations as well. Table 1 provides a list of ballistic missiles types and their associated ranges.

Full Name	Acronym	Range (km)
Battlefield Short Range Ballistic Missile	BSRBM	<150
Short Range Ballistic Missile	SRBM	150 to <1,000
Medium Range Ballistic Missile	MRBM	1000 to <2,750
Intermediate Range Ballistic Missile	IRBM	2750 to <5,000
Intercontinental Ballistic Missile	ICBM	≥ 5,000

Table 1.   Ballistic Missile Threat Classification By Range (After George C. Marshall and Claremont Institutes 2012d)

a.   Regional Threat

Iran's current ballistic weapons arsenal contains an assortment of relevant threats as well as increased numbers of mobile regional ballistic missiles with claims of incorporated anti-missile-defense tactics and capabilities, including greater accuracy in guidance systems and new propellant applications. Recent developments in Iranian capabilities also include the launch of a solid-fuel, 2000 km MRBM (Missile Defense Agency 2012b). While other countries may possess missiles capable of long ranges, Iran has the potential to reach all of Turkey as well as parts of Eastern and Southern Europe when launching from the Iranian city Tabriz (the northernmost launch location in Iran, and therefore, the closest to Southern Europe, as seen in Figure 5).
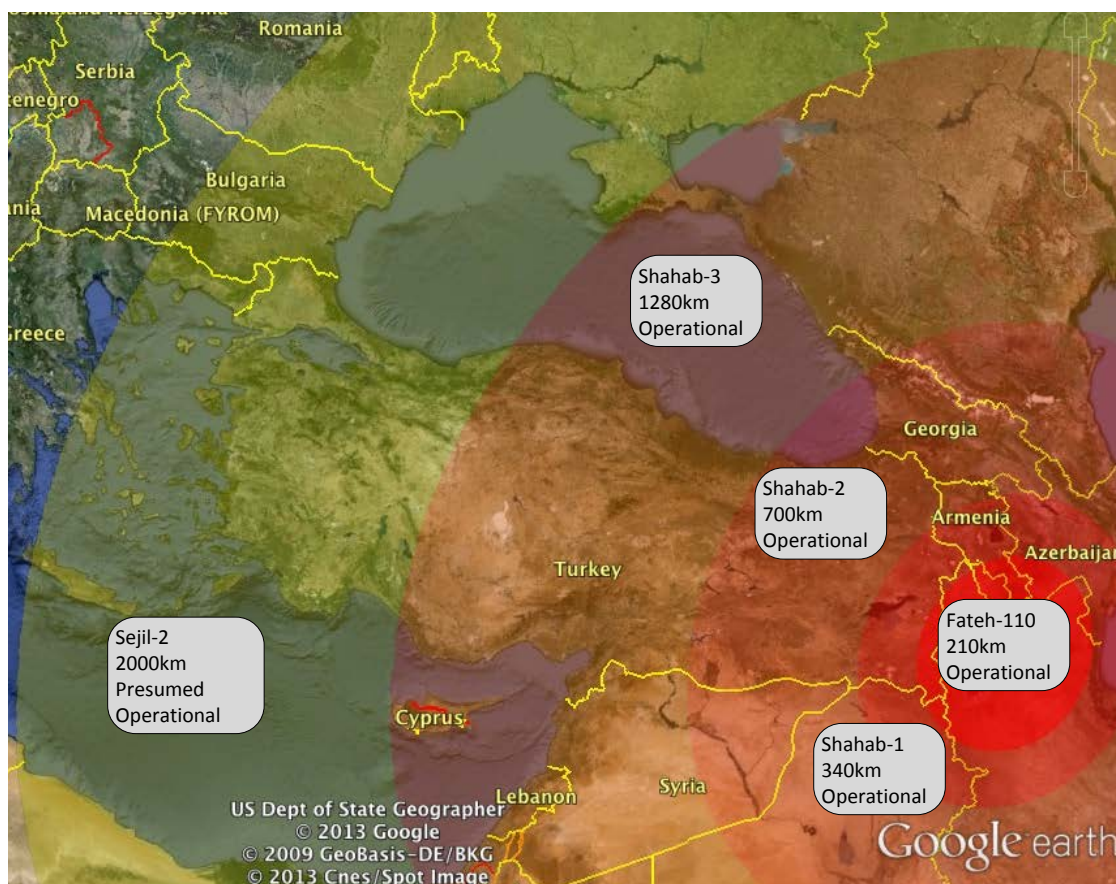
Figure 5.   Ranges of Various Iranian Ballistic Missiles as Fired from Tabriz, Iran Towards Turkey and Europe (After Google 2013). Radius Geometry Provided by FreeMapTools.com.

b.   *Operational Threats*

Iran has an extensive missile development program and has received support in the past from such countries as Russia, China, and North Korea. Iran is believed to be in possession of components from Chinese designed CSS-7 and CSS-8 SRBMs and launch systems, as well as having developed their own short range capabilities with the Fateh A-110. Much of the ballistic missile technology available to Iran is dependent upon outside sources for raw materials and components (Hildreth 2012). Current Iranian MRBM platforms are based on the North Korean No-Dong 1 ballistic missile. This technology has been improved upon with subsequent iterations resulting in operational Iranian MRBM capabilities of up to 1280 km in the case of the Shahab-3.

The Iranian Sejil ballistic missile series represents the newest and most dangerous threat from Iran. Achieving over 2000 km in tests, it extends Iran's ability to engage targets farther away such as the Greek capitol Athens (Shirzad Bozorgmehr 2009). This represents a significant increase in capability due to the range and the use of solid fuel instead of liquid. The importance of this is seen in the missile preparation time before launch. If the fuel resides in the missile at all times, as is the case with the Sejil, then once it is moved into position and given guidance information, it can be launched. With liquid fuel, the missile has to additionally be fueled before it can be launched, thus giving some warning of impending launch. A detailed matrix of ballistic missile threat characteristics is in Appendix A: Problem Space Exploration Data.

Within the current arsenal of ballistic missiles, the Shahab-3 and Sejil-2 make up the greatest threat to European NATO countries, allies, and regional U.S. forces by exhibiting the largest payload capabilities and range (White House 2012). Iran was identified as the primary regional threat (Research Question 1). The maximum ranges of these operational missiles vary from 200 km to 2000 km, as shown in Figure 6.
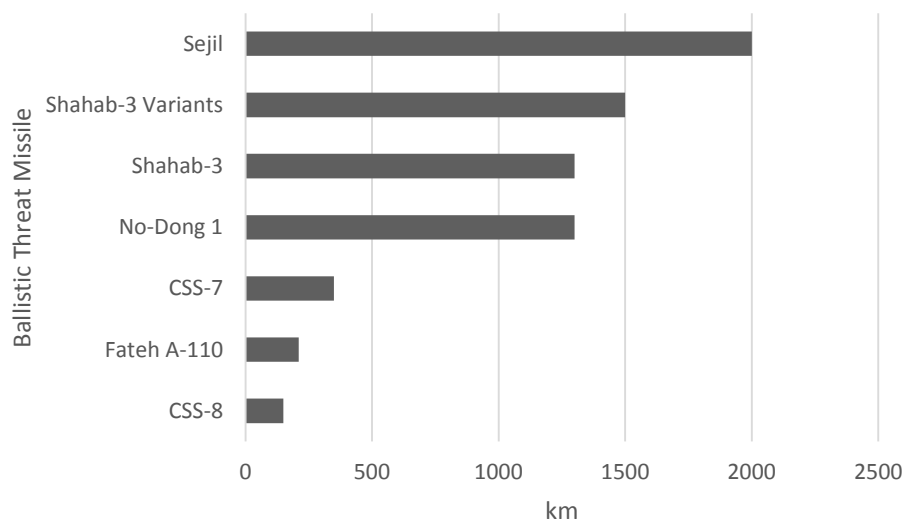
Figure 6.   The Maximum Range of Iranian and North Korean Operational Threat Missiles

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Although Iran has exhibited continual development for longer range ballistic missile capabilities, the accuracy of current ballistic missile designs is limited due to immature sensor technology. As Elleman observed:

> A large inventory of missiles would be expected for use if the desired outcome of the threat nation was to destroy a specific fixed target. Due to a current lack of nuclear warhead technology, conventional attacks are expected to result in lower casualty levels, with a smaller amount of affected areas. (Elleman 2012)

The relation of payload weight to maximum range should be considered when determining the threat to possible NATO European targets. "With an increased payload weight on a given missile, the effective strike range of   that   missile   is   decreased accordingly" (Vick 2012).

Thus, while maximum claimed strike ranges are known, placing a large conventional or even nuclear warhead could potentially reduce those claimed distances, increasing the importance of focusing on Turkey.

c.   Developmental Threats

Iran is seen as pursuing longer-range ballistic missiles by developing additional variations of the Shahab and Sejil platforms. These developmental efforts would provide Iran with IRBM range and ICBM capabilities. Iran was reported to have launched an Omid satellite via a Safir-2 rocket, or Space Launch Vehicle (SLV) in early February 2009, raising concerns based on dual-use capabilities applied toward long range missile development (Hildreth 2009). In addition to attempts to increase its threat range, Iran continues to develop SRBM and MRBM technologies with new solid-propellant designs and accuracy improvements based on sensor development (Cappacio 2012).

d.   Threat Refinement

Several factors led to the selection of Iran as the threat country of focus. One reason is its close proximity to a member of NATO, Turkey. By sharing a border, it is able to bring to bear its entire missile arsenal in a conflict as even the shortest range will still hit Turkey. As discussed, the Sejil series missiles have demonstrated in testing

that it has a maximum range of 2000 km, providing the ability to strike past Turkey and into other European countries. Also, the rhetoric from the government indicates that Iran is also ready and willing to launch its weapons. For these reasons it was selected as the focus.

e.   *Future Uncertainty*

Technology does not stand still, and as a corollary, nations continually strive to update their defensive and offensive capabilities. Thus, ballistic missile threats are going to increase both in quantity and quality as more and more countries pursue these technologies (Secretary of Defense 2010). These developments will also serve to increase flexibility, mobility, survivability, and reliability of these threats. The research efforts of threat nations will also help them improve distance, warhead, and sensor array capabilities (including navigation technology). All of these uncertainties place an increasing number of NATO and European areas at risk.

2.   Missile Defense System Concepts

To aid in understanding the basic concepts of missile defense, this section provides an overview of the missile defense process and basic functions the systems must perform to intercept a ballistic missile. In addition, the phases of the ballistic missile flight are defined.

All elements of the EBMD system work together to respond to a limited ballistic missile attack directed against NATO, our European allies and interests. The early warning system detects the launch of ballistic missile threats and tracks them continually providing data to the Battle Command Network (BCN). This function of exchanging information along the network is outside the system context, however, there will be data exchange between the EBMD system and the BCN system while ground-based radars acquire and track the incoming missile. The BCN system uses this information to make an engage decision and assigns the targets to individual interceptor systems. The BCN provides the engage decision to the interceptor systems; the interceptor systems engage the targets and provide notification the engagement is underway. The BCN continues to process system data to provide more information to the interceptor and the interceptor

uses this data to aid discrimination between debris, false objects, and real warheads. The interceptor uses its sensors to acquire the ballistic missile threat, select the target, and guide itself to the target. During and after the engagement, the radars continue to collect data during the intercept to provide damage assessment and provide the data to the BCN that evaluates the interceptor's success or failure (U.S. Department of Defense 2004).

Many types of interceptors and countermeasures for missiles exist, but the cohort limited their analysis to kinetic interceptors, i.e., those interceptors that eliminate threats on collision through their kinetic energy. For examples of non-kinetic missile defense systems, the MK-36 Super Rapid Bloom Offboard Countermeasures Chaff (SRBOC) system launches chaff to create false signals to disorient threat missiles (Federation of American Scientists 1999a), and the AN/SLQ-32 shipboard electronic warfare system attacks the missile electronically (Federation of American Scientists 1999b). These technologies were targeted against radar-guided cruise missiles; however, this report focuses on ballistic missiles which use stellar or inertial guidance systems which are not subject to electromagnetic interference (Federation of American Scientists, 2000a). With the focus on ballistic missiles, the cohort found kinetic interceptors to be effective and relevant to current threats.

The early warning system provides an awareness that an incident of concern has occurred. The early warning system then determines whether the incident is really something that the defense must address (Mantle 2004). Space-based, early warning satellites, which use heat-sensing detectors to detect missile launches while still in the boost phase, have been deployed by the U.S. for many years. The U.S. has committed to an upgraded version of these sensors (Gansler 2010).

The BCN collects and integrates threat information from Global BMD assets. During an engagement, the individual EBMD component systems constantly communicate with the BCN providing updated threat information to the BCN as well as receiving situational awareness outside the system boundaries from the BCN. By integrating the individual EBMD component systems, the BCN provides status across the overall EBMD system and provides an integrated ballistic missile defense picture (Missile Defense Agency 2013a). The BCN functions can be performed by systems such

as the U.S. Command, Control, Battle Management, and Communication (C2BMC) system or the NATO equivalent Air Command and Control System (ACCS).

Once the early warning system provides awareness to an incident of concern, the detection system determines whether the incident is truly a ballistic missile launch and if the threat is something the system should track. Detection can be queued by the early warning system (through the BCN) or independently by the detection system. The question that this detection system must answer is: "Is this a ballistic missile threat of certain speed and range, and is it headed in the direction of the defense system such that it will be able to engage it?" (Mantle 2004).

The control system refines the threat information and determines a fire control solution while continuing to track the ballistic missile threat. The system function discriminates the actual threat warhead from any accompanying countermeasures deployed to confuse and defeat the defense (Mantle 2004). When a threat leaves the atmosphere, aerodynamic drag becomes negligible and objects will tend to continue on the same ballistic path until they reenter the atmosphere. The control system discriminates the warhead from any items traveling along the same trajectory, whether these items are purpose-based countermeasures or merely missile debris. Once the system performs the functions through discrimination, performance analysis based on the characteristics of the threat is performed. The system continually updates these parameters through tracking. As a result of the control system's determinations and performance analysis, a defense strategy is calculated and individual defense interceptors are identified.

The engagement systems perform interception of the threat, performance of battle damage assessment, and readiness of the BMD system for continued engagement. Within the engagement system, individual systems initiate necessary actions after direction and notification of such actions for the purpose of neutralizing the threat. Interceptors can be launched in salvos or in shoot-look-shoot firing doctrine. Launching interceptors in a salvo consists of a simultaneous launch of multiple interceptors. The shoot-look-shoot firing doctrine represents a consecutive launch pattern. After a first shot (a shot defined by either a single interceptor or a salvo of interceptors) is fired, the defense system

determines whether the incoming missile was hit or missed before the decision to launch a second shot is made. Such a technique allows the defense system to analyze the need for a follow-on shot, thus providing the ability to economize the inventory of interceptors (Mantle 2004).

Since ballistic missiles threats, and the interceptors designed to defeat the threats, have different ranges, speeds, size and performance characteristics, BMD is normally performed in a layered approach providing multiple opportunities to destroy threats before they reach their targets (Missile Defense Agency 2013a). The first definition of layered centers on the ranges and locations of the interceptors. Mantle describes these layers as "a lower-layer system to provide point defense around key assets; an upper-layer system to defend a wide area encompassing the key assets; a forward-based system to intercept the threat early in its flight." (Mantle 2004, 55)

In another definition of layered defense, the threat engagement occurs at any of the three phases of flight along a ballistic trajectory. Intercept occurs in three phases: boost, midcourse, and terminal. All three phases require the similar characteristics for successful intercept, accurate threat tracking, appropriate reaction times relative to engagement phase, and advanced interceptors with reliable communications and advanced sensors (Cepak 2005).

a.   Boost Phase

The boost phase of a ballistic missile deployment represents the earliest point of engagement, providing the most amount of time for reengagement should the interceptor miss. In the boost phase, the engine of the ballistic missile threat provides thrust to send the ballistic missile into and out of the atmosphere. Early detection is possible in the boost phase because the missile engine exhaust allows infrared sensors to detect the heat signatures (Cepak 2005). Fast detection is also possible with dedicated radar systems such as the AN/TPY-2 forward stationed (Missile Defense Agency 2013a).

Another early action consideration applicable to the boost phase is interception/destruction. By intercepting the target or destroying through non-kinetic means it would provide the ability to neutralize a ballistic missile threat prior to

deployment of any countermeasure technology. This may result in a reduction of necessary interceptor inventories as no response to countermeasures (decoys) would be required. Due to the boost phase being defined as prior to apogee, within a given trajectory, the amount of potential debris and location of the debris field may also be minimized (Missile Defense Agency 2013a). The defense by early interception is limited by the availability of capable systems, however possible elements include Airborne Laser (ABL) and Kinetic Energy Interceptor (KEI) technology (Missile Defense Agency 2007). Other potential technologies include the use of Unmanned Aerial Vehicles (UAV) being employed for local detection in over-the horizon sensor netting capabilities.

b. *Midcourse Phase*

The midcourse phase begins upon missile booster burnout and occurs outside the earth's atmosphere. This is typically the longest phase of ballistic missile flight with the flight path determined by the initial trajectory at booster burnout and the pull of gravity. During midcourse phase, a ballistic missile threat may deploy decoys and it is likely booster debris will surround the ballistic missile requiring the BMD system to discriminate the threat (Cepak 2005). Both the Ground-Based Midcourse Defense and Aegis ship elements are available and capable of defense against ballistic missile threats ranging from short to long-range ballistic missiles. The BCN provides detection and tracking of missile threats and associated countermeasures across various assets. (Missile Defense Agency 2013e). This phase offers the BMD system several possible opportunities to engage ballistic missile threats.

c. *Terminal Phase*

The terminal phase defense is often characterized by lower altitude, rapid response systems. The characteristic intercept range of these systems is defined as short- to medium-range. The terminal phase begins when the threat renters the atmosphere and is the last opportunity to intercept the ballistic missile's flight prior to reaching the target. The ballistic missile threat may conduct final maneuvers during the terminal phase. (Cepak 2005).

3.   Existing BMD System Components

Threat mitigation may require a mix of land, air, sea, and space capabilities. Solutions may require closely coordinated, joint and combined efforts. These efforts may need to build on existing systems and doctrine, and when appropriate, incorporate the newest technologies and concepts. Decisions regarding acquisition of unique EBMD systems must be weighed carefully against resource constraints and mission needs. The following identifies the existing components and identifies existing solutions (Research Question 3) that might be considered in BMD planning. These systems may be compared to the functional needs and, if functional needs are met, included in the functional architecture of the solution. The following identifies some existing components that currently accomplish global ballistic defense. The list provided aids in understanding the concepts and is not intended to provide specific solutions to the EBMD problem.

a.   *Ground-Based Interceptor Systems*

Ground based intercept systems currently in theater are placed near troop deployments, command centers, and civilian population centers, providing the first approach to engage ballistic missile threats in theatre. The PAC-3 and THAAD use this approach for BMD (Gansler 2010). The PAC-3 provides simultaneous air and terminal phase missile defense capabilities and is currently deployed by the U.S. Army (Missile Defense Agency 2013f). THAAD provides a terminal phase intercept capability that is rapidly deployable and operates in both the endo/exo-atmospheric regions. THAAD received Conditional Material Release and is transitioning operations to the U.S. Army (Missile Defense Agency 2013g).

b.   *Sea Based Interceptor Systems*

The sea is another possible deployment location for BMD systems and sea-based interceptor systems work well for defense of the fleet. In addition, sea-based interceptors can be expanded to protect ground-based assets as a mobile launch platform readily deployed for use in boost phase interception of ballistic missile threats when in close proximity to the threat launch site. Depending upon the characteristics of a ballistic

missile threat, a sea-based system could also be used against any of the phases of an ICBM (Gansler 2010).

Aegis ships are the sea-based component of BMDS and provides the capability to defeat short and intermediate range ballistic missile threats with the Standard Missile-3 (SM-3). As of November 2012, there are 26 Aegis combatants with 16 assigned to the Pacific Fleet and 10 assigned to the Atlantic Fleet (Missile Defense Agency 2013h).

c. Detection Systems

The AN/TPY-2, the Space Tracking and Surveillance System (STSS), the Sea-Based X-Band (SBX) Radar, and Upgraded Early Warning Radars (UEWR) currently conduct ballistic missile threat detection.

The AN/TPY-2 is an X-band, high-resolution, phased-array radar designed to detect and track all classes of ballistic missiles and is transportable by air, ship, truck and rail. The AN/TPY-2 provides detection, tracking and fire control support functions for the THAAD weapon system (Missile Defense Agency 2013i).

The MDA operates the STSS, which consists of two satellites orbiting at 1350 km with a 120-minute orbital period, and serves as the experimental space layer of the BMD system. The STSS carries sensor capable of detection in the shortwave IR band and can provide early warning detection in the boost phase. Other sensors allow the STSS to track threats in the midcourse phase of ballistic flight (Missile Defense Agency 2013j).

The SBX is an advanced X-band radar mounted on an ocean-going, semi-submersible platform that detects and tracks ballistic missiles. The SBX provides tracking information while an incoming ballistic missile threat is in flight. The SBX is capable of discriminating the threat from debris and decoys that accompany a ballistic missile warhead. The SBX system then provides that information to a battle command function or interceptor system to intercept the ballistic missile threat before reaching its intended target. Mounting the SBX on an ocean-going platform, allows global coverage by repositioning the platform (Missile Defense Agency 2013k).

The UEWR provides early warning, detection, classification, and tracking of ballistic missiles. The UEWR are solid-state, phased array, all weather, long range radars that operate in the Ultra High Frequency Band to provide detection of objects out to 3000 miles. There are currently three UEWR systems. The UEWR system in Flyingdales, United Kingdom (Missile Defense Agency 2013l) is capable of detecting ballistic missile threats to Europe.

While each of these components is highly capable and important to ballistic missile defense, none can accomplish all the functions of an effective ballistic missile defense system. Effective ballistic missile defense must utilize these various capabilities in concert, and the architecture of that system is much more difficult to orchestrate than that of the constituent components.

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III. REQUIREMENTS ANALYSIS

A. THE REQUIREMENTS PROCESS

There existed a need to identify a clear set of requirements in order to successfully arrive at a solution. With the needs of the stakeholders clearly identified, the cohort performed a requirements analysis to provide an in-depth view of the capabilities that would drive potential solutions. The cohort implemented a process of iterative requirements generation and analysis in concert with the initial functional analysis, modeling and simulation analysis, life cycle cost analysis, and analysis of alternatives (Figure 7).

The cohort used input from the problem space exploration process to capture the top level requirements. The top level requirements were decomposed into lower level requirements. Iteration was built into the model to allow for requirements refinement. The refined requirements then served as input for the functional analysis. The iteration was not confined to only the requirements analysis, but rather continued on into the functional analysis.
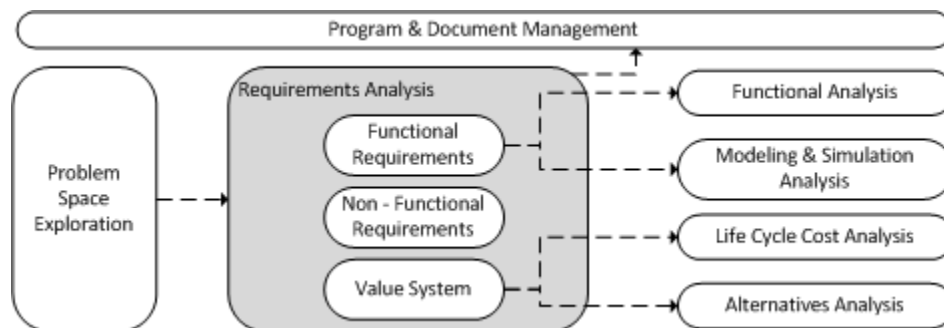
Figure 7.   The Requirements Analysis Process

B. FUNCTIONAL REQUIREMENTS

The EBMD functional requirements defined the capabilities that the EBMD system must be able to accomplish. The functional requirements consisted of six high level requirements that the EBMD system must perform to successfully counter a ballistic missile threat. These six high level requirements were decomposed into lower level

support requirements that more clearly defined the capability the EBMD system must perform. The detect requirements in Table 2 originated from the need to detect a ballistic missile threat. It is paramount that the system be able to detect multiple ballistic missile threats simultaneously and discriminate between friend and foe to satisfy any subsequent requirements. This was due to the fact that the ballistic missile threats may be a salvo of ballistic missiles that must be detected and eventually controlled and engaged simultaneously.

The detect requirements came from the cohort's mission needs analysis as well as *A Technical Assessment of Iran's Ballistic Missile Program* (Postol 2009). The speeds and sizes were established using data found in Chapter II, Section C: Mission Need Analysis.

Requirement	Description
1	The EBMD system shall detect potential ballistic missile threats. This requirement is further refined by:
1.1	The EBMD system shall allow no more than 10% undetected potential ballistic missile threats at a 90% confidence level.
1.2	The EBMD system's simultaneous detection capability shall be able to discriminate between multiple threats 98% of the time at a 90% confidence level.
1.3	The EBMD system shall have a 97% probability of detection at a 95% confidence level.
1.4	The EBMD system shall have a 99% probability of friend/foe distinction with 90% confidence level that a friendly is not mistaken for a foe.
1.5	The EBMD system shall have a false alarm probability of 0.005 $\frac{false\ targets}{targets\ detected}$ or less.
1.6	The EBMD system shall be able to detect up to five ballistic missiles at a time.
2	The EBMD system shall detect potential ballistic missile threats of varying sizes and speeds. This requirement is further refined by:
2.1	The EBMD system shall be able to detect ballistic missile threats as small as 8.8m length and 0.6m width.
2.2	The EBMD system shall be able to detect ballistic missile threats at speeds of 2.0–2.5 km/s.
2.3	The EBMD system shall be able to detect potential ballistic missile threats early enough to make a firing decision before maximum intercept range has been met.

Table 2.   Detect Function Requirements

The control function requirements in Table 3 determined the physical characteristics of possible ballistic missile threats. These requirements allowed the system to identify the specific ballistic missile threats and provide the appropriate means necessary to counter that threat. These requirements also originated from the need for early flight threat detection.

Requirement	Description
3	The EBMD system shall be able to determine the threat profile in a timely manner. This requirement is further refined by:
3.1	The EBMD system shall be able to determine the size of the potential ballistic missile threats with an accuracy of 5% the actual size.
3.2	The EBMD system shall be able to determine the speed of the potential ballistic missile threats with an accuracy of 5% the actual speed.
3.3	The EBMD system shall be able to determine the anticipated impact location with an accuracy of +/-100m the actual impact location.

Table 3.　　　Control Function Requirements

The rationale for the engage requirements in Table 4 came from both the Mission Need Analysis and the Missile Threat Matrix described in Marshall and Claremont Institutes (George C. Marshall and Claremont Institutes 2013a). According to *Iran's Ballistic Missile and Space Launch Programs*, Iran has multiple missile silos and launchers (Hildreth 2012). The possibility of a salvo attack needed to be taken into consideration.

Requirement	Description
4	The EBMD system shall be able to engage a threat. This requirement is further refined by:
4.1	The EBMD system shall be able to engage no less than 90% of the incoming ballistic missile threats at a 90% confidence level.
4.2	The EBMD system shall provide the capability to abort the target engagement.
4.3	The EBMD system shall be able to engage up to five ballistic missiles at a time.

Table 4.　　　Engage Function Requirements

The assess requirements of the engage function in Table 5 originated from the need for accurate battle damage assessment, and is necessary to the protection of the defended footprint. The EBMD system must be able to discern whether or not a follow-on engagement is necessary, and if so, it must be able to engage in a timely manner. The following assess requirements apply to salvo attacks as well as individual ballistic missile attacks.

Requirement	Description
5	The EBMD system shall be able to assess the battle damage to ascertain whether or not another defensive engagement is necessary. This requirement is further refined by:
5.1	The EBMD system shall report whether or not the threat(s) has been completely eradicated.
5.2	The EBMD system shall be able to discern if a follow on engagement is possible after previous attempt.
5.3	The EBMD system shall evaluate whether or not a defensive engagement was successful with 90% confidence.

Table 5.   Assess Function Requirements

The communication requirements in Table 6 were essentially the glue that held the various EBMD assets together. Continuous, reliable, and secure communication among the EBMD system, the Battle Command, and the interceptor missile is critical. Although the Battle Command and BCN were outside the context of our system, it was important enough to develop requirements that would allow the EBMD system to communicate to ensure the Battle Command maintains situational awareness.

Requirement	Description
6	The EBMD system shall be able to maintain communication with assets necessary to carry out its BMD mission. This requirement is further refined by:
6.1	The EBMD system shall maintain communication links with the missile and battle command network at least 99% of the time.
6.2	The EBMD system shall maintain communication links between the battle command network and early warning system at least 95% of the time.

Table 6.   Communication Function Requirements

C.   NON-FUNCTIONAL REQUIREMENTS

The non-functional requirements in Table 7 are the quality attributes that helped define the EBMD system. Unlike the functional requirements, the non-functional requirements were not taken into consideration during modeling and simulation (M&S). These requirements are often referred to as the "-ilities." Other non-functional requirements define certain environmental conditions that the system is likely to face and must withstand.

Requirement	Description
7	The EBMD system shall be reliable, available, and maintainable in order to perform BMD missions. This requirement is further refined by:
7.1	The EBMD system shall have an operational availability of no less than the operational availability of existing BMD architectures which comprise the integrated EBMD system. This operational availability is for the overall system including missiles, sensors, C2 centers, and associated electronics and support equipment.
7.2	The EBMD system shall have a Mean Time Between Failure (MTBF) of no less than the MTBF of existing BMD architectures which comprise the integrated EBMD system.
7.3	The EBMD system shall have a Mean Time To Repair (MTTR) no greater than the MTTR of existing BMD architectures which comprise the integrated EBMD system.
8	The EBMD system shall have minimal impact on manpower. This requirement is further refined by:
8.1	The EBMD system shall have no more than a 10% increase in manpower over the current manpower level.
8.2	Training shall be provided on the EBMD system.
9	The acquisition of the EBMD system shall be within the appropriated budget for EBMD. This requirement is further refined by:
9.1	The EBMD system shall leverage, to the maximum extent possible, technology that will decrease acquisition cost while maintaining or increasing operational mission capability.
9.2	The EBMD system shall minimize the number of personnel required for system operation.
10	The EBMD system shall comply with the latest revision of MIL-STD-810.
10.1	The EBMD system shall be able to withstand vibration by complying with the latest revision of MIL-STD 810.
10.2	The EBMD system shall be able to withstand shock by complying with the latest revision of MIL-STD 810.
10.3	The EBMD system shall be able to withstand rain and blowing rain by complying with the latest revision of MIL-STD 810.
10.4	The EBMD system shall be able to withstand icing and freezing rain by complying with the latest revision of MIL-STD 810.
11	The EBMD system shall incorporate mobility.

Table 7.   Non-Functional Requirements

The interoperability requirements in Table 8 originated from the need to ensure that EBMD systems, when collocated with each other or with other forms of friendly communication systems, undergo no degradation in performance. The EBMD systems

cannot have capabilities that are compromised due to communication delays or interference. Unlike the communication requirements that are concerned with the communication necessary among the various EBMD assets within a single system, the interoperability requirements are concerned with communication among multiple EBMD systems as well as joint service friendly C4ISR systems while maintaining the effectiveness of said systems. The interoperability requirements are in place to ensure we do not degrade the performance of any other systems in the area, to include other EBMD systems.

Requirement	Description
12	The EBMD system shall be operable in the presence of EMI, friendly missile defense systems, and friendly communication systems. This requirement is further refined by:
12.1	The EBMD system shall be interoperable with neighboring EBMD systems.
12.2	The EBMD system shall be interoperable with current and projected service, joint, NATO, and combined missile defense and C4ISR systems.
12.3	The EBMD system shall interoperate with all collocated friendly communication systems.
12.4	The EBMD system shall comply with the latest revision of MIL-STD 461.

<div align="center">Table 8.　　　Non-Functional - Interoperability Requirements</div>

The information assurance requirements (Table 9) originated from the need to safeguard critical system information from inadvertent or malicious technology transfer to unauthorized users. The need to ensure information integrity as well as denying unauthorized access to EBMD system information are also drivers for the information assurance requirements.

Requirement	Description
13	The EBMD system shall possess physical security, operational security, and information assurance measures. This requirement is further refined by:
13.1	The EBMD system shall comply with DoD physical security policies and procedures.
13.2	The EBMD systems shall use standard DoD cryptographic equipment rather than require unique designs.
13.3	The EBMD system shall comply with the latest revision of the National Information Assurance Policy on the Use of Public Standards for the Secure Sharing of Information Among National Security Systems of the Committee on National Security Systems Policy, CNSSP-15.

<div align="center">Table 9.　　　Non-Functional - Information Assurance Requirements</div>

D.　VALUE SYSTEM

The EBMD value system defined and organized the Evaluation Measures (EMs) upon which alternative analysis was based. The value system defined the most important aspects of the system based on the Stakeholder Analysis and the Mission Need Analysis.

Those processes along with the EMs provided our cohort with a means to measure the ability of the alternatives to meet the operational needs of the overall EBMD system.

Of primary concern to our stakeholders, and thus our cohort, was the ability of the EBMD system to *engage and neutralize threats*. At its simplest, the ability of the EBMD system to successfully perform its mission was a combination of the overall effectiveness of the system to detect, control, and engage potential ballistic missile threats, and being able to communicate among the various elements of the EBMD system. This evaluation measure was evaluated through the *Probability of Intercept*, P_i. The probability of intercept for the baseline and each EBMD Alternative came from both the calculations in Chapter VI, Section B: Determining the Probability of Intercept, and the simulations in Chapter VI, Section C: Scenario Based Simulation.

Following the probability of intercept in our value system was *Percent Footprint Defended*, P_{fd}. The EBMD system must be able to defend Turkey. The extent to which the EBMD Alternatives defend the whole of Turkey was a basis for analysis: the greater the area of Turkey that was defended by at least one layer of protection the better. This evaluation measure was evaluated through the *Percent Footprint Defended*, P_{fd}. The percent footprint defended for the baseline and each EBMD Alternative came from Scenario Based Simulations.

The ability to engage and neutralize threats as represented by P_i, and P_{fd}, comprised the EMs that were used to compare the EBMD Alternatives in Chapter IX. The metric of P_i was the best way to quantitatively measure, through modeling and simulation, the ability of the EBMD system to engage and neutralize a potential ballistic missile threat. M&S also quantitatively measured and provided metrics for the second EM of P_{fd}.

The Evaluation Measures are as follows:

EM	Description
P_i	Probability of Intercept
P_{fd}	Percent Footprint Defended

Table 10.   Evaluation Measures

Probability of Intercept, P_i, is defined as the probability of the EBMD system to successfully engage a threat. Percent Footprint Defended, P_{fd}, is defined as the ratio of defended area to the area intended to be defended. The final aspect of the EBMD top level requirements is the Life Cycle Cost (LCC). During Analysis of Alternatives in Chapter IX, the LCC of the Baseline and EBMD Alternative systems were ultimately incorporated into a decision evaluation display for analysis in relation to the EMs in Table 10.

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IV. FUNCTIONAL ANALYSIS

A. FUNCTIONAL ANALYSIS PROCESS

After the requirements were compared to the high level stakeholder needs, a functional hierarchy was laid out to ensure all functional requirements were captured. The functional requirements then fed into the functional analysis approach (Figure 8).
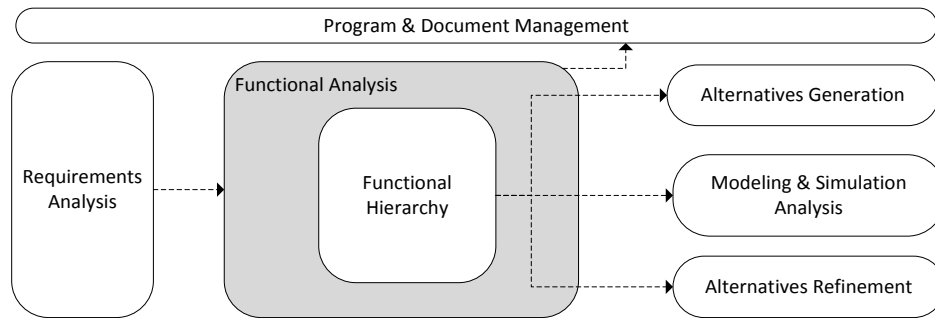
Figure 8. Functional Analysis Process

The functional analysis provided the basis for the initial alternatives generation process that later supported the M&S process.

B. MODELING THE FUNCTIONS

Vitech Corporation's CORE software was used for EBMD top level function development, including the functional hierarchy and enhanced functional flow block diagrams (EFFBD) (Vitech Corporation 2013). Both model views are provided in the report so the reader can take advantage of visualization differences to have a better understanding of the system.

CORE was chosen as the software tool because of its comprehensive modeling environment designed for complex systems engineering problems. Model-based systems engineering tools like CORE provide some advantages over simple drawing tools like Microsoft's Visio. The greatest advantage was the ability to change one portion or view of the model, and see that change propagate throughout the entire model. With a little practice, when making changes, the cohort was able to switch through multiple views to

better understand the impacts of changes. This was advantageous while developing the functional hierarchy and EFFBDs. If a particular view was required to develop specific concepts, that view was used and compared against the other dynamic views for possible impacts to the overall system.

While traceability is considered an advantage of CORE (all requirements and functions are linked), the cohort found it easier to use Microsoft Excel spreadsheets to show traceability between the functions and the requirements. This adaptation would most likely not scale though, and CORE may have an advantage in such situations.

CORE also provided the cohort with preferred methods to communicate the results. Instead of having multiple files, all the information is contained in one "model" that could be analyzed in many different views simply by a few mouse clicks. In addition, the specific views could be easily edited for communication purposes without changing the actual details of the model. This cannot be done in Microsoft's Visio or similar products.

The top level requirements were laid out in CORE and used as the basis for the development of the top level functions. The top level functions were further refined by lower level functions that directly support the realization of the functional hierarchy.

C.   LEVERAGING THE FUNCTIONAL ARCHITECTURE VIEWS

Linking of the functions' inputs, outputs, and triggers was performed in CORE and is listed in subsequent descriptions to provide an overview of the functional architecture. The EFFBD displays the order that these transformations occur by providing the flow of each function. This order is necessary to create the final functional output. The EFFBD also includes the information that is passed between each of the functions. CORE allowed the cohort to populate the same database between both the function hierarchy and EFFBD view types. This allowed the cohort to flip between models to check both the logic of data exchange and sequencing with just a click of a tab. This visual representation provided significant insight into the decisions, actions, and activities of our system.

D. SYSTEM CONTEXT

The BMD system employs local and global networks of sensors that can detect missile launches or incoming ballistic missile threats and alert active-defense systems to neutralize the ballistic missile threats. A large number of sensors and defense systems must be placed throughout the world to assess and neutralize incoming ballistic missile threats in near real-time. To address these threats to Turkey, the EBMD system uses a sub-set of these systems.

The global BMD system assets and the EBMD system are always active and are connected to the BCN. Through the BCN, information can be consolidated and provided to the EBMD system providing greater situational awareness than a stand-alone EBMD system. This does not preclude the EBMD system from acting independently; in a multiple ballistic missile threat scenario, it is expected the BCN would provide information and priorities based on the greater situational awareness that would enhance EBMD system effectiveness. Figure 9 provides the EBMD system context within the larger BMD system.
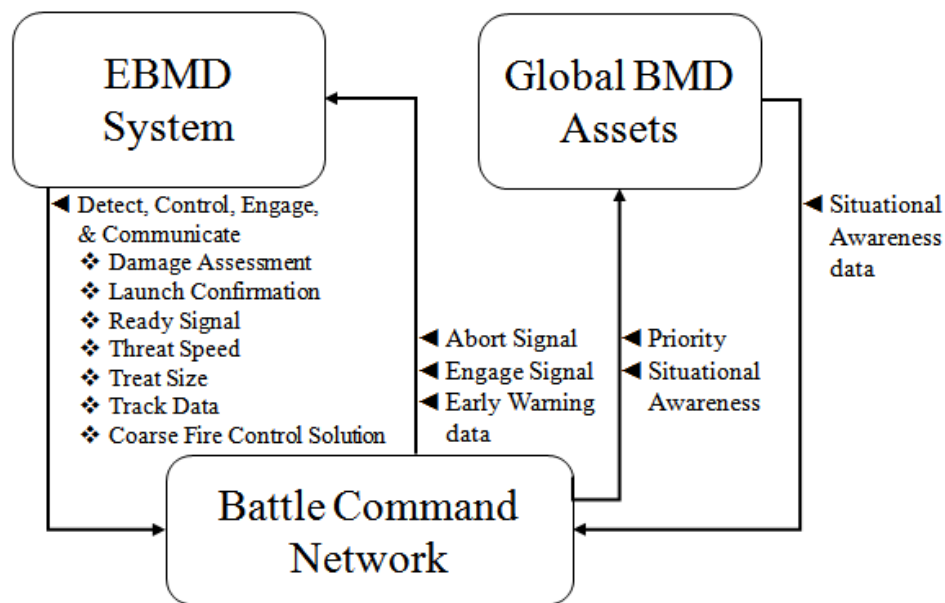
Figure 9.   EBMD System Context

E. FUNCTIONAL HIERARCHY

The functional hierarchy (Figure 10) displays the decomposition of functions from higher levels to lower levels on a single diagram, and the functional hierarchies are addressed in detail in the subsequent sections.
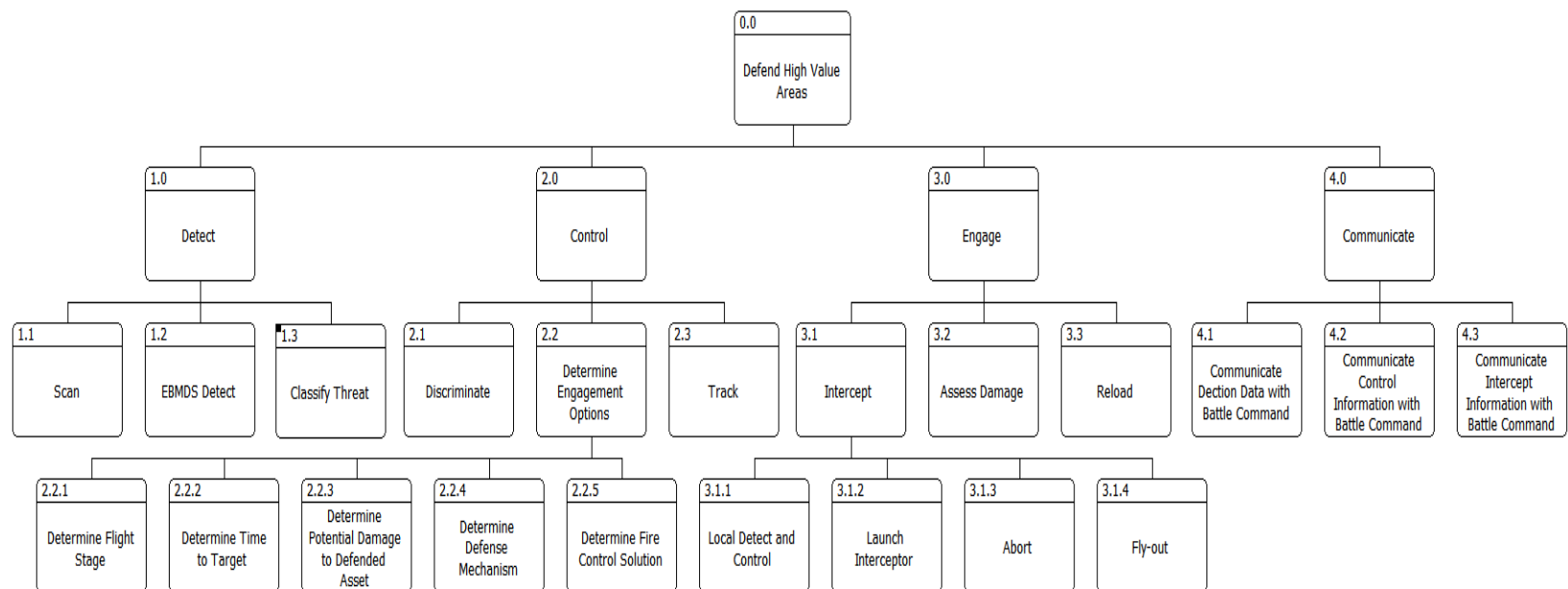
Figure 10.   EBMD Functional Hierarchy

1. Defend High Value Areas

Figure 11 illustrates the functional decomposition of the stakeholders' highest priority function, defend high value areas, into four primary second-level functions, which are detect, control, engage, and communicate information about possible ballistic missile threats.
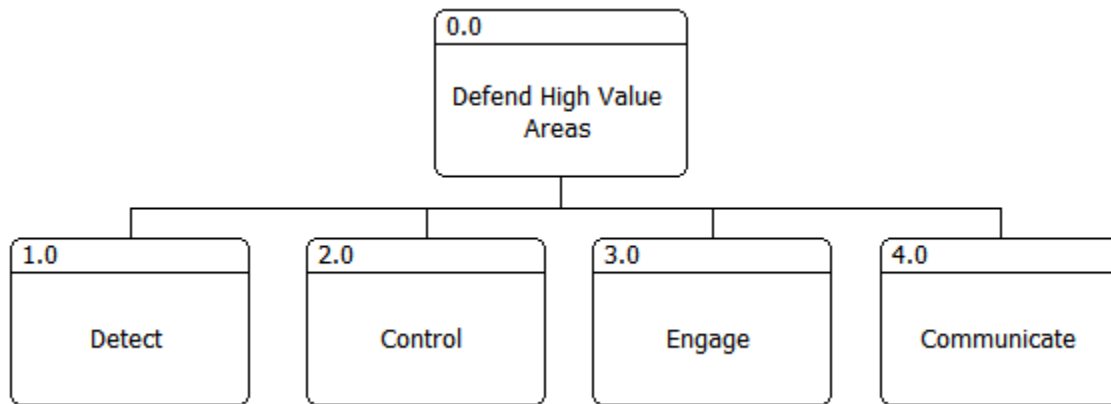
Figure 11.   Defend High Value Areas Functional Hierarchy

Figure 12 shows the EFFBD for the primary high level stakeholder need to defend high value areas. This functional flow is complicated and difficult to show in a standard EFFBD. This EFFBD represents the importance of the primary functions of detect (1.0 Detect), control (2.0 Control), engage (3.0 Engage), and communicate (4.0 Communicate) to achieving the primary goal of defending a high value area (0.0 Defend High Value Areas) against ballistic missile threats. For the purposes of this paper, the cohort looked at the top level functions to determine if a system could perform the functions required to neutralize a single ballistic missile threat. A determination if a system could be integrated into a SoS through the BCN and provide sufficient BMD performance to neutralize several ballistic missile threats will be discussed later in this paper.
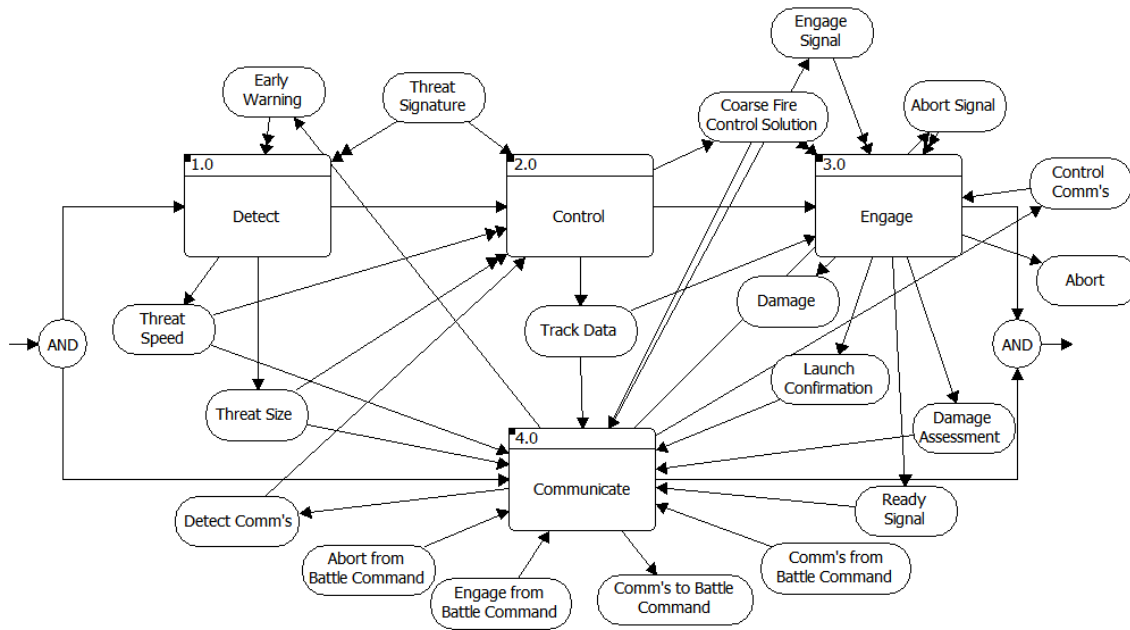
Figure 12.   Defend High Value Areas EFFBD

The detect function is triggered by either a threat signature, the environmental signature created by a possible ballistic missile, or an early warning signal, delivered by the BCN to the communicate function, to the detect function. The classify threat function determines the speed and size of the object and determines if it is a threat. If determined to be a threat, the threat characteristics are passed to the control function. The control function establishes the ballistic missile track and develops a coarse fire control solution. The control function passes both items to the engage and communicate functions.

The coarse fire control solution triggers the engage function. The engage function then causes damage to the incoming ballistic missile threat. Once the engage function engages the ballistic missile threat, it reloads and provides a ready signal to the communicate function. The BCN can provide an abort signal through the communicate function, the engage function aborts the engagement. As a result of greater situational awareness, the BCN can provide an engage signal, along with engage information, through the communicate function. This triggers the engage function to engage the

ballistic missile threat the same as the coarse fire control trigger except the engage function uses the data provided by the communicate function.

The communicate function creates a bridge to the BCN. The communicate function passes the detect items (threat speed and threat size), the control items (tracking and coarse fire control), the engage items (launch confirmation, damage assessment, and ready signal) to the BCN. The communicate function then passes the data from the lower level functions through the BCN to the battle command. The BCN is in contact with global ballistic missile defense assets and has a greater situational awareness than the standalone EBMD system. The BCN can pass additional detect, control, engage items to the communicate function and the communicate function then passes this data to the respective EBMD system functions. The respective detect, control, and engage functions then processes this data providing greater situational awareness for the EBMD system.

2.   Detect System Functional Hierarchy

Figure 13 is a depiction of the detect function. This function applies criteria that determines to some level of acceptance that the target detected is or is not a ballistic missile launch (Mantle 2004).
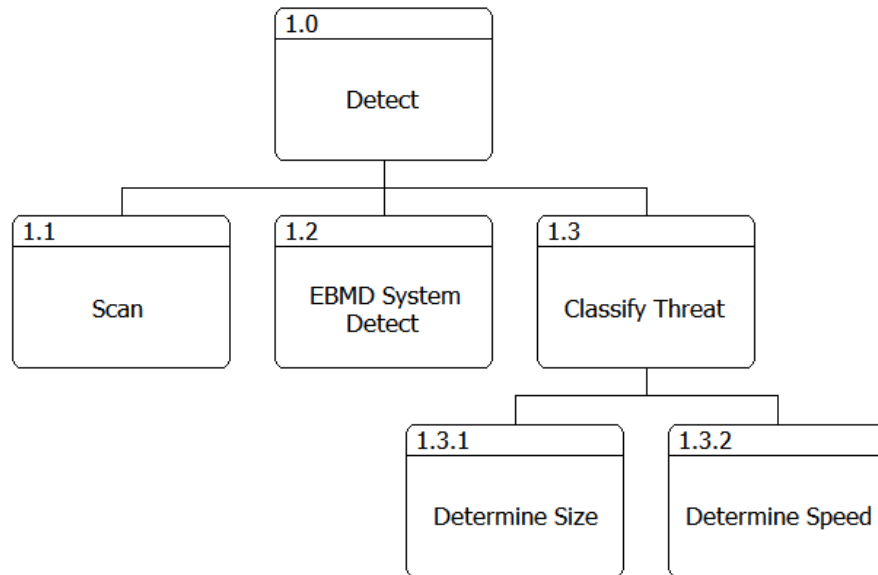
Figure 13.　　　　Detect Functional Hierarchy

The system can be alerted to a ballistic missile threat in two ways, each way having its own timing aspects. The first way is an early warning system that communicates through the BCN warning that a possible ballistic missile threat has been detected. The EBMD system then slews to the correct location and scans that area until the ballistic missile threat enters the local detection range. The second way consists of the EBMD system performing routine scans of the designated area until a possible ballistic missile threat is detected. Both ways lead to an eventual EMBD system detection and classification of the ballistic missile threat. Classification is the determination that the object detected is indeed a ballistic missile threat of concern and not a satellite launch or other benign event. A more detailed description for the detect functional hierarchy is provided in Table 11.

Function	Function Description
1.1 Scan	The scan function is required in the case that the early warning detectors do not detect the ballistic missile threat; the EMBD system will perform normal duties, such as continual scans of designated areas of the sky for possible ballistic missile threats.
1.2 EBMD System Detect	The EBMD system detect function consists of the local system detecting possible ballistic threats by the local system scanning.
1.3 Classify Threat	The classify threat function requires that the EBMD system determine if the ballistic missile detected is a threat that the defense system should be concerned about.
1.3.1 Determine Size	The determine size function establishes the size of all the objects detected in the detection system's assigned scan sector.
1.3.2 Determine Speed	The determine speed function establishes the speed of all the objects detected in the detection system's assigned scan sector.

Table 11. Detect Functions

The first overarching function is 1.0 Detect (Figure 14). This function is to determine that the anomaly "detected" is or is not a ballistic missile launch (Mantle 2004). The detect function is initiated in one of two ways, locally or through the early warning system notification from the BCN.
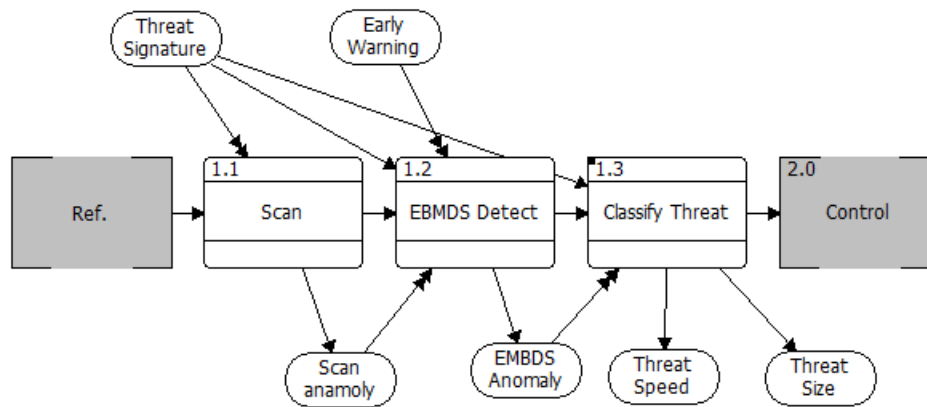
Figure 14. Detect Function EFFBD

In the first path, the local sensors scan (1.1 Scan) the surrounding area in a predetermined path best suited to detect anomalies from any suspected direction. The environmental signature from the ballistic missile threat creates an anomaly that then triggers the EBMD system to determine if the anomaly is a ballistic missile (1.2 EBMD System Detect). In the second approach, an early warning system detects a ballistic missile and passes the information to the Battle Command through the BCN. The EBMD system then skips the scanning process and starts the detect function (1.2 EBMD Detect). The detect function passes the detection information to the classifying threat function (1.3 Classify Threat) to determine if the anomaly is an object of concern. If the object is considered to be a ballistic missile threat, the classifying threat function will then determine the ballistic missile threat size (1.3.1 Determine Size) and speed (1.3.2 Determine Speed). At this point, it has been determined that the anomaly is of sufficient concern to be considered a ballistic missile threat detection and the primary detect function has been completed.

3.   Control System Functional Hierarchy

Figure 15 depicts the 2.0 Control function. The control function refines the ballistic missile threat information, determines engagement options, and tracks the ballistic missile threat.
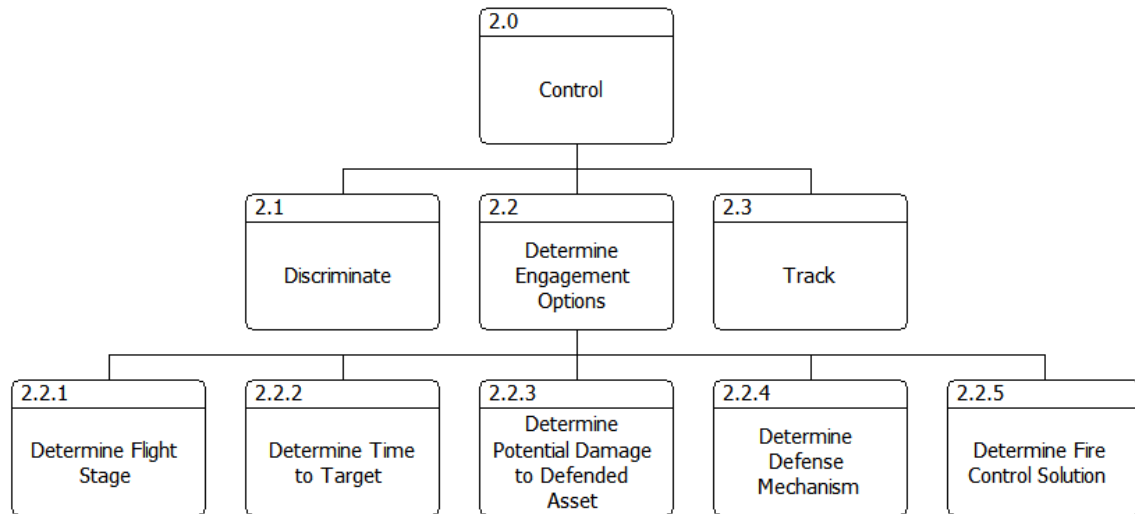
Figure 15.   Control Functional Hierarchy

The control function (Table 12) begins once the anomaly has been classified as a threat. The EBMD system discriminates the ballistic missile threat from accompanying objects meant to counter and defeat the EBMD system (Mantle 2004). This is accomplished at the local level and then the information is passed to the BCN to provide the Battle Command greater situational awareness. The control function can be completed with many systems and consolidated at the Battle Command. The Battle Command will then determine the appropriate response and transmit the required information to each location that will engage the ballistic missile threat through the BCN.

Function	Function Description
2.1 Discriminate	The discriminate function differentiates the ballistic missile threat warhead from any accompanying debris or countermeasures (Mantle 2004).
2.2 Determine Engagement Options	The determine engagement options function calculates what systems can be used to engage and successfully defeat the ballistic missile threat.
2.2.1 Determine Flight Stage	The determine flight stage function determines at which stage the ballistic missile threat is in; boost, midcourse, or terminal, and at which layer; exo, end-exo, or endo atmospheric.
2.2.2 Determine Time to Target	The determine time to target function determines how long it will take the ballistic missile threat to reach its estimated target.
2.2.3 Determine Potential Damage to Defend Asset	The determine potential damage to defend asset function estimates the amount of damage that the ballistic missile threat could inflict to the high value area. This information is then transmitted to the Battle Command through the BCN to provide situational awareness.
2.2.4 Determine Defense Mechanism	At the local level, the determine defense mechanism function calculates which components will engage the ballistic missile threat.
2.2.5 Determine Fire Control Solution	The determine fire control solution function consists of developing the fire control solution for each ballistic missile threat location involved in the engagement. This will be at the resolution of the detection sensor carrying out the function.
2.3 Track	The track function establishes the path of the threat to predict the future position at a given time and continuing this until the object is defeated or is no longer considered a threat.

Table 12.　　　Control Functions

Figure 16 is the EFFBD for the 2.0 Control function. In the control function, the ballistic missile threat is understood well enough to predict its future path and determine an engagement option.
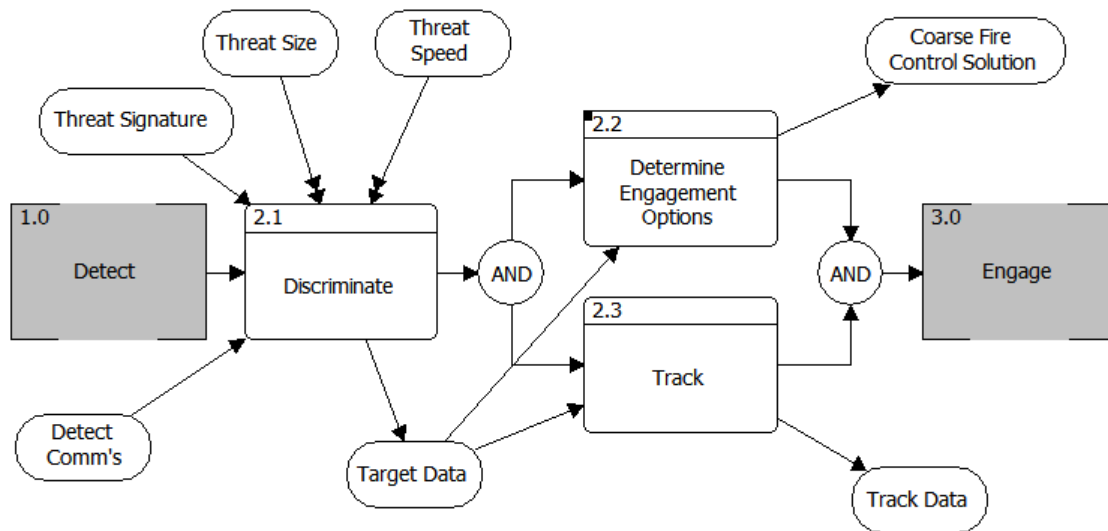
Figure 16.   Control Function EFFBD

The Control function (2.0 Control) begins when the detect function provides the ballistic missile threat classification data. The Discriminate function (2.1 Discriminate) then differentiates the ballistic missile warhead from the surrounding materials such as shrouds or decoys. The tracking function (2.3 Track) ensures that the data received is valid and repeatable enough so that the data can be used to predict the future path of the ballistic missile threat. Simultaneously, available engagement options are determined by the Determine Engagement Options (2.2 Determine Engagement Options as seen in Figure 17).
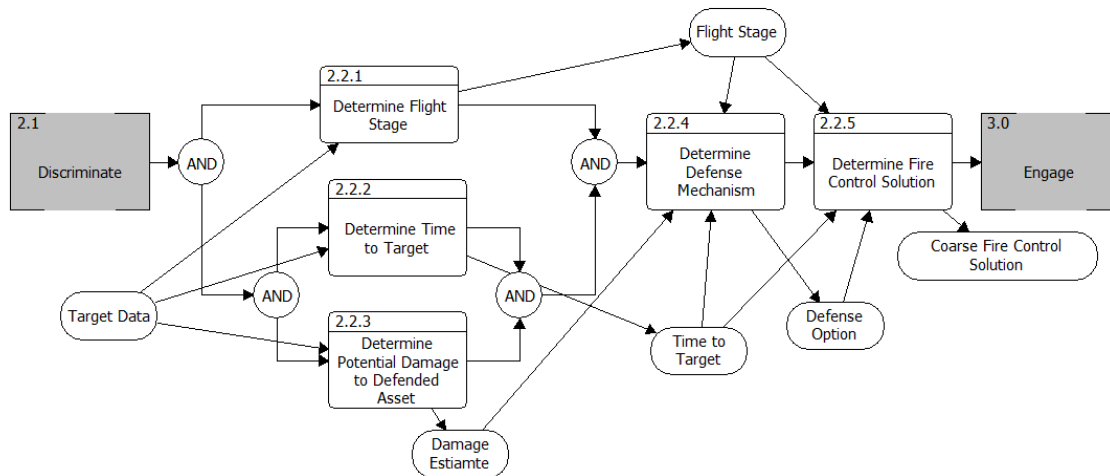
Figure 17.   Determine Engagement Options Function EFFBD

This is accomplished by determining the stage the threat is in, such as boost, midcourse, or terminal (2.2.1 Determine Flight Stage), the time left until the ballistic missile threat impacts the target (2.2.2 Determine Time to Target), and the damage that can be caused (2.2.3 Determine Potential Damage). Once these parameters are defined, the Determine Defense Mechanisms function (2.2.4 Determine Defense Mechanism) determines the best defense mechanism and a fire control solution (2.2.5 Determine Fire Control Solution) is calculated. All the information determined during the control phase is passed to the communicate function and then to the Battle Command through the BCN for compilation with other components and further processing. The Battle Command can also pass data to the EBMD system through the BCN and to the EBMD system communicate function. This ensures that the global BMD system maintains real-time situational awareness.

4.   Engage System Functional Hierarchy

The Engage Function (3.0 Engage) is depicted in Figure 18. As discussed earlier, the Battle Command receives information from several sources and determines the best course of action. The Battle Command triggers the engage function by transmitting a coarse fire control signal and tracking information. The EBMD system then engages and neutralizes the ballistic missile threat.
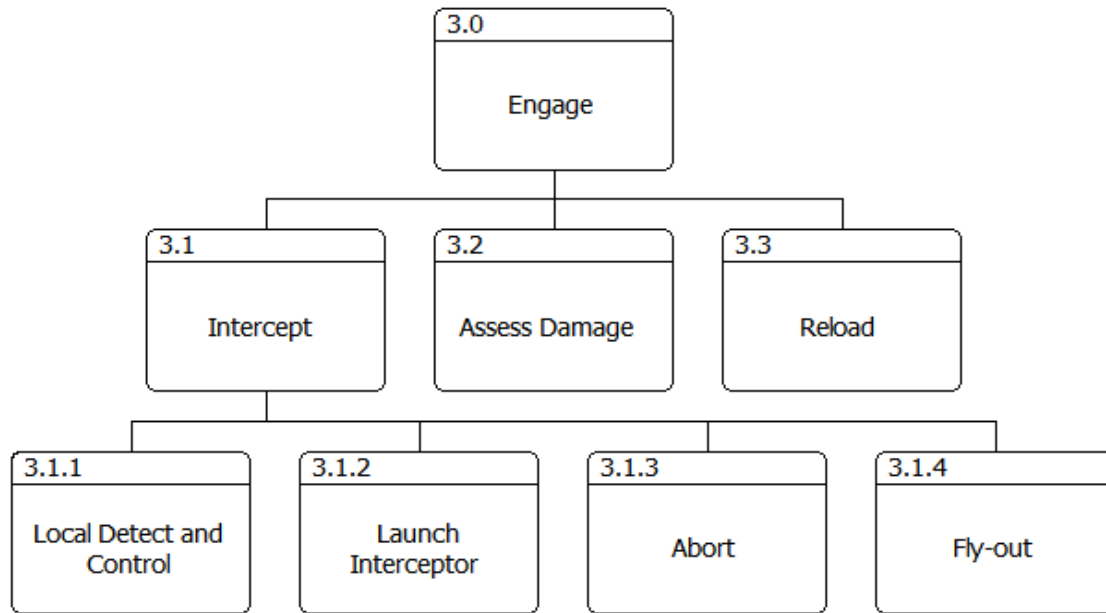
Figure 18.   Engage Functional Hierarchy

The engage function (Table 13) will occur once an object is detected and verified to be a ballistic missile threat. The Battle Command will then make the determination to engage the ballistic missile threat.

Function	Function Description
3.1 Intercept	The intercept function launches an interceptor at the determined ballistic missile threat.
3.1.1 Local Detect and Control	The local detect and control function refines the fire control solution provided by the BCN or the local system.
3.1.2 Launch Interceptor	The launch interceptor function loads the fire control solution into the interceptor, confirms the solution is loaded, and launches the interceptor.
3.1.3 Abort	The abort function aborts the launch sequence.
3.1.4 Fly-out	The fly-out function determines if the interceptor is clear of the launcher and is on course to engage the ballistic missile threat.
3.2 Assess Damage	The assess damage function performs a battle damage assessment and that information is passed to the communicate function and then provides that information to the Battle Command through the BCN for greater situational awareness.
3.3 Reload	The reload function prepares the system for another engagement after an interceptor launch and alerts the intercept function that the system is ready for another engagement.

Table 13.   Engage Functions

Figure 19 is the EFFBD for the engage function (3.0 Engage). The intercept function is triggered by either the control function passing the coarse fire control solution or by the communicate function providing an engage signal. If the communicate function triggers the intercept, the intercept function uses the control data provided by the communicate function to engage the ballistic missile threat. Regardless of triggering method, the intercept function creates a launch confirmation signal that triggers the reload function. Once reload is complete, the reload function sends a ready signal back to the intercept function.
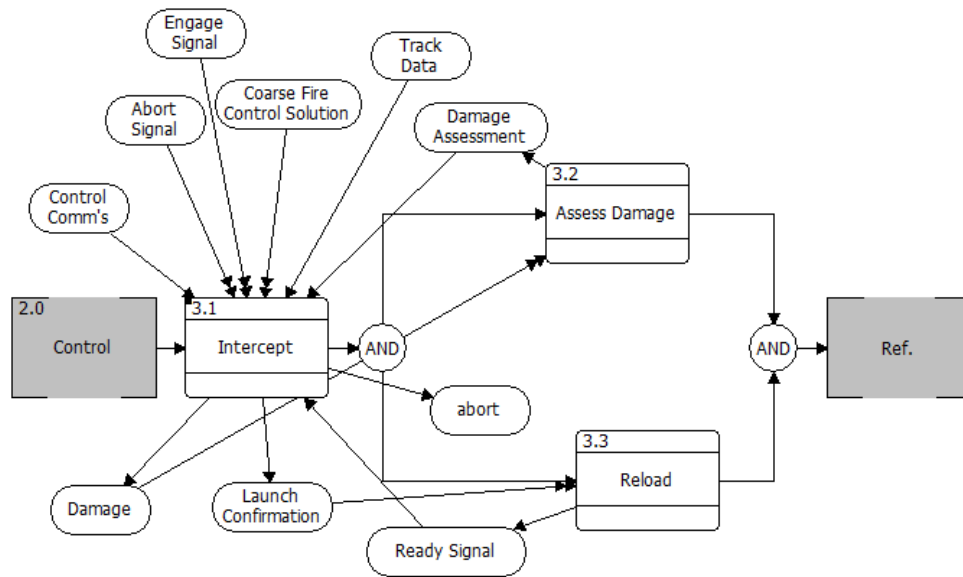
Figure 19.   Engage Function EFFBD

Once the interception function has begun, the EBMD system receives the control information and performs all the functions necessary to perform the detect and control functions at the local level if it has not already occurred. It should be noted, this could have already occurred if the BCN does not provide any additional information. Once the EBMD system algorithms provide a refined fire control solution (3.1.1 Local Detect and Control), an interceptor launches (3.1.2 Launch Interceptor). Once the interceptor is launched, the Battle Command is notified through the BCN, and has the option to abort the launch (3.1.3 Abort) or continue with the engagement (3.1.4 Fly-out). These functions are displayed in Figure 20.
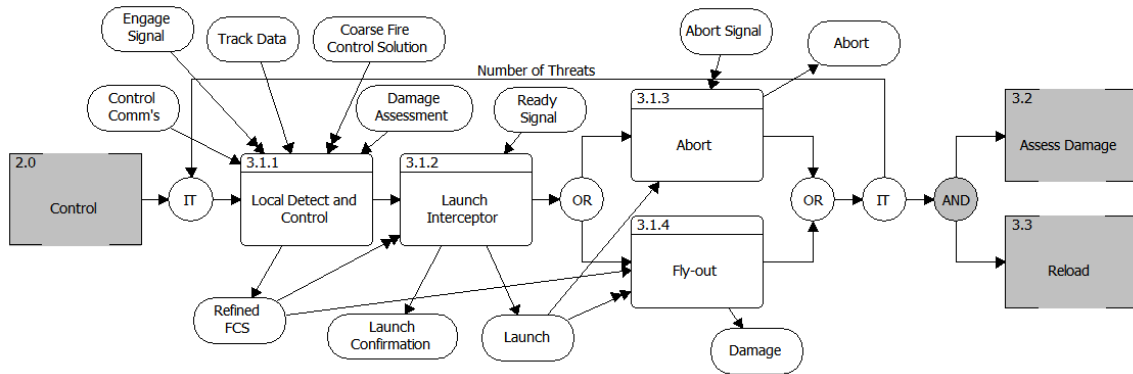
Figure 20.   Intercept Function EFFBD

After the interceptor reaches the ballistic missile threat and some level of damage is inflicted, the damage assessment function (3.2 Assess Damage) calculates the amount of damage the ballistic missile threat received and, if necessary, a reload occurs (3.3 Reload). At this point the reload function provides a ready signal back to the intercept function.

5.   Communicate System Functional Hierarchy

Figure 21 is a depiction of the 4.0 Communicate function. The communicate function consists of all the communication functions that occur between the system components and the Battle Command through the BCN.
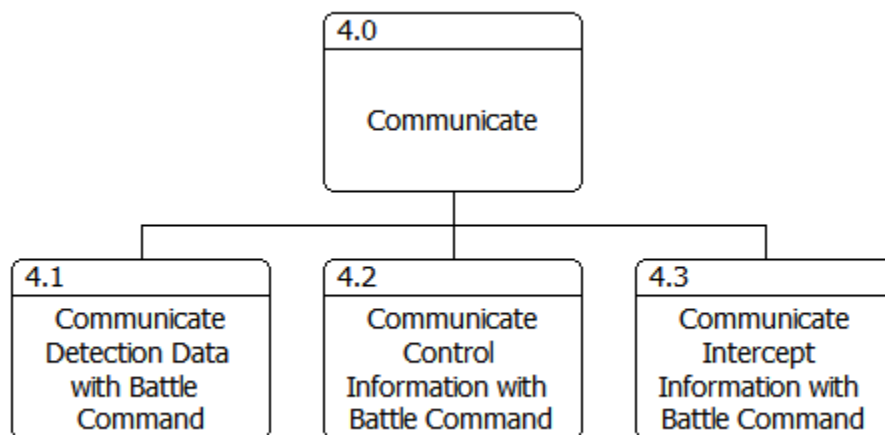
Figure 21.   Communicate Functional Hierarchy

Since the Battle Command and the BCN are outside the context of the EBMD system, the individual EBMD system components will communicate (Table 14) to Battle Command throughout an engagement to ensure the Battle Command maintains situational awareness. The communicate function captures all communications occurring continuously from start to finish.

Function	Function Description
4.1 Communicate Detection Data with Battle Command	The communicate detection data with Battle Command function alerts the Battle Command during the detect functions.
4.2 Communicate Control Information with Battle Command	The communicate control information with Battle Command function communicates information during the control functions.
4.3 Communicate Intercept Information with Battle Command	The communicate intercept information with Battle Command function is the communications that occur during the intercept functions.

Table 14.   Communicate Functions

The communication function (4.0 Communicate), shown in Figure 22, occurs throughout the EBMD system components. This is shown at high levels as the communication of detection data (4.1 Communicate Detection Data), communication of control information (4.2 Communicate Control Information), and communication of intercept information (4.3 Communicate Intercept Information).
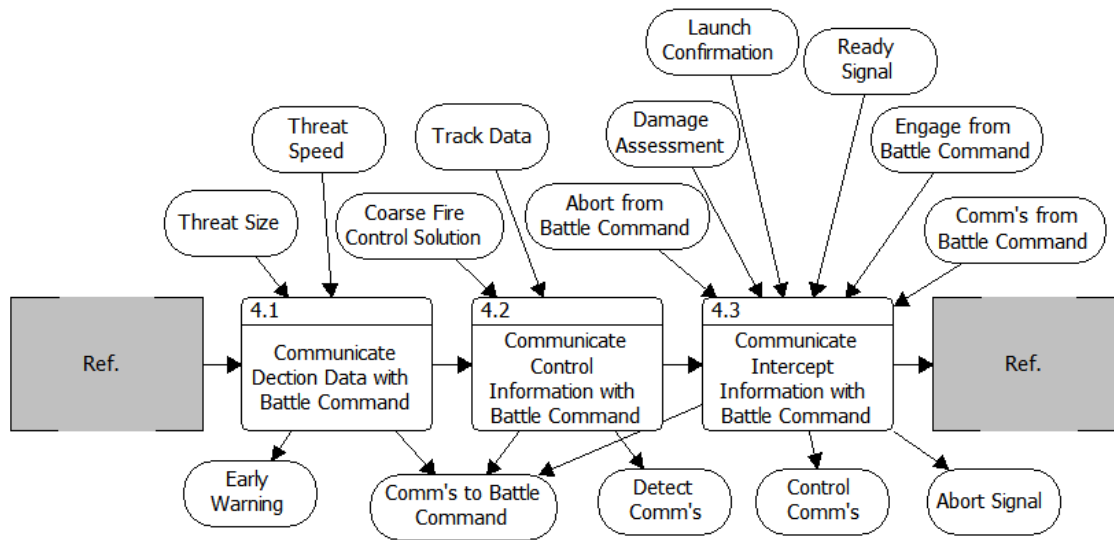
Figure 22. Communicate Function EFFBD

All this data is handled by the three main communication functions (4.1 Communicate Detection Data with Battle Command, 4.2 Communicate Control Information with Battle Command, and 4.3 Communicate Intercept Information with Battle Command). This process allows the Battle Command to maintain real-time situational awareness of any detected anomalies that may be a threat of concern.

F. REQUIREMENTS TO FUNCTIONS TRACEABILITY

A top level requirements mapping to functions is provided in Table 15. This mapping shows that each requirement is addressed by at least one function in the functional hierarchy. Each function in the functional decomposition does not necessarily map to a specific requirement, however each function is required for system operation. The mapping of requirements to functions ensures that each requirement is at least mapped to a function that can accomplish that specific requirement.

Requirement	Requirement Description	Function
1	The EBMD system shall detect potential ballistic missile threats.	1.0 Detect
1.1	The EBMD system shall allow no more than 10% undetected potential ballistic missile threats at a 90% confidence level.	1.0 Detect
1.2	The EBMD system's simultaneous detection capability shall be able to discriminate between multiple threats 98% of the time at a 90% confidence level.	2.1 Discriminate
1.3	The EBMD system shall have a 97% probability of detection at a 95% confidence level.	1.0 Detect
1.4	The EBMD system shall have a 99% probability of friend/foe distinction with 90% confidence level that a friendly is not mistaken for a foe.	1.3 Classify Threat
1.5	The EBMD system shall have a false alarm probability of $0.005 \frac{false\ targets}{targets\ detected}$ or less.	1.0 Detect
1.6	The EBMD system shall be able to detect up to five ballistic missiles at a time.	1.2 EBMD System Detect
2	The EBMD system shall detect potential ballistic missile threats of varying sizes and speeds.	1.0 Detect
2.1	The EBMD system shall be able to detect ballistic missile threats as small as 8.8m length and 0.6m width.	1.3.1 Determine Size
2.2	The EBMD system shall be able to detect ballistic missile threats at speeds of 2.0–2.5 km/s.	1.3.2 Determine Speed
2.3	The EBMD system shall be able to detect potential ballistic missile threats early enough to make a firing decision before maximum intercept range has been met.	1.0 Detect
3	The EBMD system shall be able to determine the threat profile in a timely manner.	1.3 Classify Threat
3.1	The EBMD system shall be able to determine the size of the potential ballistic missile threats with an accuracy of 5% the actual size.	1.3.1 Determine Size
3.2	The EBMD system shall be able to determine the speed of the potential ballistic missile threats with an accuracy of 5% the actual speed.	1.3.2 Determine Speed

Requirement	Requirement Description	Function
3.3	The EBMD system shall be able to determine the anticipated impact location with an accuracy of +/-100m the actual impact location.	2.2.3 Determine Potential Damage to Defended Asset
4	The EBMD system shall be able to engage a threat.	3.0 Engage
4.1	The EBMD system shall be able to engage no less than 90% of the incoming ballistic missile threats at a 90% confidence level.	3.0 Engage
4.2	The EBMD system shall provide the capability to abort the target engagement.	3.1.3 Abort
4.3	The EBMD system shall be able to engage up to five ballistic missiles at a time.	3.0 Engage
5	The EBMD system shall be able to evaluate battle damage assessment in order to ascertain whether or not another defensive launch is necessary.	3.2 Assess Damage
5.1	The EBMD system shall report whether or not the threat(s) has been completely eradicated.	4.3 Communicate Intercept Information with Battle Command
5.2	The EBMD system shall be able to discern if a follow on engagement is possible after previous attempt.	3.2 Assess Damage
5.3	The EBMD system shall evaluate whether or not a defensive engagement was successful with 90% confidence.	3.2 Assess Damage
6	The EBMD system shall be able to maintain communication with assets necessary to carry out its BMD mission.	4.0 Communicate
6.1	The EBMD system shall maintain communication links with the missile and battle command network at least 99% of the time.	4.0 Communicate
6.2	The EBMD system shall maintain communication links between the battle command network and early warning system at least 95% of the time.	4.0 Communicate

Table 15.   Requirements To Functions Traceability

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V. ALTERNATIVES GENERATION

A. ALTERNATIVES GENERATION PROCESS

Due to the current budget constraints in the DoD, it was assumed that neither the Army nor the Navy has the resources to develop new systems needed to support this mission. Therefore, this report addresses alternatives using existing weapon systems that are currently under development and planned for fielding within the project timeframe. As described in Chapter II, Section C: Mission Need Analysis, interceptors were limited to kinetic-kill versions. The cohort selected systems currently fielded or envisioned by the U.S. to defend Europe: Aegis ships, THAAD, PAC-3, and AN/TPY2. The planned Aegis Ashore system was also examined. A mapping of the high-level functions to components is provided in Table 16. Performing a mapping of the functions to components during the alternatives generation process (Figure 23) provided a viable set of components for use in M&S, and alternatives refinement, and ensured that the components used in the simulation could perform the necessary functions for BMD.
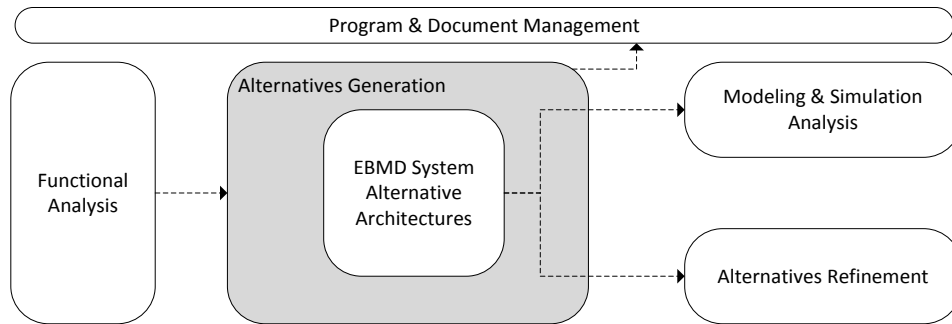
Figure 23.   Alternatives Generation Process

For example, the THAAD system uses the AN/TPY-2 in order to perform the required detect and control functions for BMD.

Component	Function			
	Detect	Control	Engage	Communicate
Aegis Ship	X	X	X	X
THAAD			X	X
PAC-3	X	X	X	X
AN/TPY-2	X	X		X
Aegis Ashore	X	X	X	X

Table 16. Functional Mapping to Components

B. COVERAGE OF ALTERNATIVES

By acting together as a SoS, the various defense systems can achieve broader coverage and more appropriate responses by coordinating information through the BCN, which resides outside the scope of this analysis. As an example, Lewis and Postol calculate the AN/TPY-2 radar to have a detection range of approximately 870 km and calculate the Aegis AN/SPY-1 radar's detection range at a shorter 550 km. (Lewis and Postol 2012b). The detection range of the PAC-3's AN/MPQ-65 radar is stated to go up to 170 km (Army Recognition 2013). The AN/TPY-2's broader range allows for wider coverage and earlier detection, allowing the most appropriate interceptor battery to engage the threat.

The EBMD Baseline represents the currently fielded ballistic missile defense capabilities. At the time of this report, EUCOM had two BMD capable Aegis ships in the Mediterranean, an AN/TPY-2 Radar and six PAC-3 batteries in Turkey (United States European Command 2012b; Defense Industry Daily 2013b; North Atlantic Treaty Organization 2013). Modeling and simulation feedback on the Baseline system provided two important conclusions: the Baseline system does not meet the requirements and the PAC-3 is so limited in range and performance that, for the sake of this analysis, it was not capable of intercepting a ballistic missile. Therefore, alternatives to this Baseline system needed to be more capable in order to meet the requirements and the PAC-3 was omitted in the alternatives.

Alternatives were generated by identifying which components were capable of performing BMD (either alone or paired to another system) and performing M&S to

determine the performance of the configuration. Based on the alternative system performance in M&S, components were moved, added or removed to meet the requirements while trying to keep the total number of systems, and in turn the total cost, to a minimum. The quantities and placements of components were categorized into three alternatives and a general approach for each alternative is provided in Table 17. The general approach for each alternative was provided to M&S for further analysis to determine approximate locations and quantities of components necessary to meet the requirements.

Alternative	Description
A	Vary the number and placement of Aegis ships
B	Vary the number and placement of Aegis ships and THAAD to meet the requirements
C	Explore the use of an Aegis Ashore alone, and with Aegis ships and/or THAAD if necessary to meet the requirements

Table 17. General Approach for Each EBMD Alternative

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VI. MODELING AND SIMULATION ANALYSIS

A. MODELING AND SIMULATION ANALYSIS PROCESS

During the M&S process (Figure 24), the results of the problem space exploration process, including threat components, BMD components, BMD concepts and technical details, were incorporated into the construction of models. These models operated functionally identical to the functional hierarchies and flows (as close as practically possible within the confines of the modeling tools) identified during functional analysis. The models were also constructed to ensure they could meet the evaluation measures from the requirements analysis process and match the component architectures identified during alternatives generation. The initial analysis determined the probability of intercepting a threat missile, P_i, which was used in the analysis of the various alternatives that followed the M&S effort. The scenario-based simulation process then simulated those alternatives and generated data to further refine alternatives that were used to evaluate performance parameters.
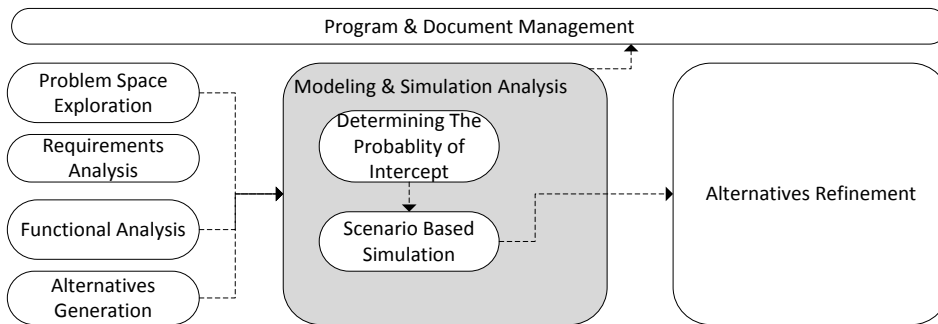
Figure 24.   Modeling And Simulation Analysis Process

B. DETERMINING THE PROBABILITY OF INTERCEPT

The probability of intercept is the key effectiveness measure identified during requirements analysis, but the functional analysis lacks the quantitative data necessary to directly derive its value. The cohort determined it by examining the interaction of component systems in the EBMD Alternatives and by using the probabilities of intercept

for individual BMD component systems. Although high confidence values for the probabilities of intercept of the component systems are understandably classified, there is an abundance of unclassified test data available to develop a reasonable set of approximations.

The cohort used Aegis component system test data from as far back as 2008 (O'Rourke 2013) to determine probability of intercept. The number of fully successful tests (no misses), divided by the total number of tests (10/14), yields a calculated probability of intercept of 0.713 (O'Rourke 2010; Defense Industry Daily 2013a). The ratio of successes to failures looks like it may be increasing with newer versions (Under Secretary of Defense 2010). Battlefield values are expected to be lower than controlled test data.

The PAC-3 is the latest version of the Patriot anti-missile system. Earlier versions of the Patriot missile system are the only U.S. ballistic missile defense systems with intercept estimates based on combat use (Jeremiah D. Sullivano 1999). Initial estimates of probabilities of intercept for earlier versions of the Patriot anti-missile system (not the PAC-3) after the Gulf War gave the system very high probabilities of intercept (Simon 1996). Within ten years after an initial positive assessment, the DoD issued a report in 1992 that stated, "We have found no convincing evidence in the video that any Scud warhead was destroyed by a Patriot" (Lewis and Postol 1992, 12). It is difficult to generate much confidence from such a large range of estimates.

The cohort used intercept test data to draw an initial probability of intercept and chose a standard value for all of the three component interceptor systems (Aegis, THAAD and PAC-3). The initial value for component system probability of intercept is 0.713. This initial value is the source probability used in the following scenario-based M&S.

This probability of intercept scales with increased depth of coverage. With one layer of coverage, the system's probability of intercept equaled the initial probability of intercept. Overlapping coverage of several component systems or engaging the ballistic

missile threat with multiple interceptors from a single component system achieved increased depth.

However, the layering depth is achieved, the increased effectiveness, as measured by an increased probability of intercept, will scale according to a simple binomial distribution. When the system is engaging a single missile the binomial distribution reduces to a simple product of probabilities. The probability of a "leaker" for a layer is one minus the probability of intercept for that layer (where a leaker is considered an undetected ballistic missile threat). The probability of leakers for a multi-layered system is the product of the probability of leakers for all the layers. Since all the layers in this situation have the same probability of leakers, the probability of leakers for a multi-layered example is simply the probability of leakers for a single layer raised to the power of the number of layers. The probability of intercept for the multi-layered system is one minus the probability of leakers for the multi-layered system.

$$(1.1) \qquad P_{i\,system} = 1 - \prod_{component=1}^{Layers} P_{l\,component} = 1 - \left(1 - P_{i\,component}\right)^{Layers}$$

In equation 1.1, $P_{i\,system}$ is the probability of intercepting the missile by the system, $P_{l\,component}$ is the probability of leakage (missing the missile) for a component, and $P_{i\,component}$ is the probability of a component intercepting the missile. The value for *Layers* in this case is the number of components as each component system comprises a layer. Table 18 shows the probabilities of intercept given different layer depths.

Number of Layers	Probability of Intercept
0	0
1	0.713
2	0.918
3	0.976
4	0.993

Table 18.　　　Probability of Intercept Given Depth of Layers

C. SCENARIO BASED SIMULATION

In addition to the discrete element simulation, the cohort performed scenario-based M&S using an integrated M&S software package called Systems Tool Kit (STK) from Analytical Graphics, Inc (AGI). A scenario is a project a user has set up to model, or, as defined by STK, "an instance of an analytical or operational task that you are modeling with STK" (Analytical Graphics Incorporated 2013). The scenario-based M&S effort was facilitated by use of the Missile Modeling Toolkit (MMT) STK plugin, also provided by AGI.

STK and MMT were used to provide a relatively rapid time to determination of ballistic missile trajectories and interception capabilities. The equations to calculate trajectories with a rotating planet can be very difficult. Further complicating the mathematics are moving interceptor batteries such as those found on Aegis ships. STK allowed relatively easy setup, modeling, and animation of scenarios and performed all requisite calculations automatically to determine flight trajectories and intercepts.

1. Systems Tool Kit (STK)

STK was chosen for its mission modeling, visualization and its ability to accept plugins that enhance the BMD related functionality of the software. This helped to simplify the assessment of the EBMD system.

STK "scenarios" allow for creation and placement of many types of objects on two-dimensional (2D) or three dimensional (3D) models of the Earth such as facilities, satellites, ships, missiles, etc. Numerous properties and relationships are assigned to these objects. These objects can also be assigned activities such as routes or orbits that allow them to interact where appropriate. Once defined, the scenario is animated to show the modeled movements and interaction among the components if defined.

STK also computes "access" between objects, enabling the modeler to determine timing and location of interaction between objects. For example, the access between incoming threat missiles and radar coverage can be computed to determine when the radar first detects a threat missile and how long it tracks the missile. This access can also

be used to determine if sufficient time exists between the first detection of a threat missile and the launch of an interceptor.

2. Missile Modeling Tools (MMT)

STK also provides a back end platform to extend functionalities to dozens of plugins and modules. Through the use of plugins, missile flight and intercept capabilities were simulated and analyzed, which was critical for analysis of the EBMD system. MMT, developed by Science Applications International Corporation (SAIC) and supplied by AGI, provided the ability to analyze missile flight and intercept capabilities.

The MMT plugin is a suite of four related applications to model missile-related activities. These applications are the Missile Design Tool (MDT), Missile Flight Tool (MFT), Interceptor Flight Tool (IFT), and the Missile Conversion Tool (MCT). The MCT was not necessary for modeling and analysis of the EBMD system. The four applications are depicted in Figure 25. The MMT workflow is as follows:

1. Create missiles or interceptors with MDT.
2. Test the missile's flight in MFT and test the interceptor's ability to engage the threat missiles in IFT.
3. Export it all to STK for animation and visualization.
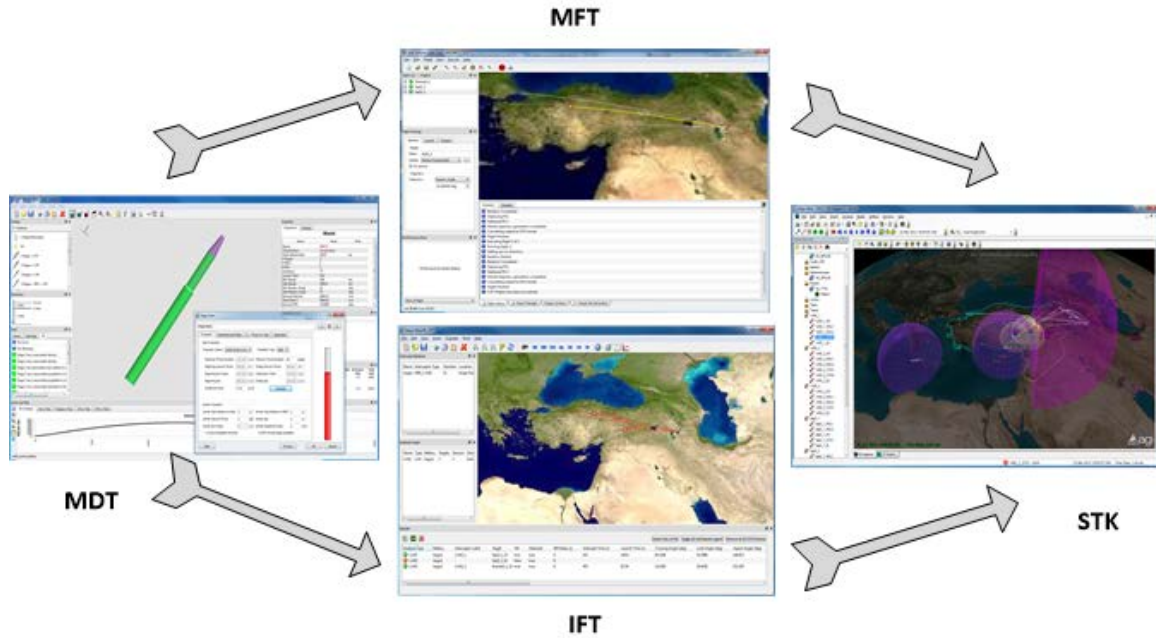
Figure 25.   MMT Workflow

a.   *Missile Design Tool (MDT)*

MDT was used to create new missile models when generic models built in to the MMT applications were not representative of the real-life missile type. These custom models were then exported to IFT and MFT. Custom interceptors were created by adding or removing components and defining the characteristics. A software wizard assisted in creating the missiles or interceptors. Even when using the wizard, it was often necessary to refine the properties such as the dimensions and masses of the missile stages, the amount of propellant, and the propellant burn rate and specific impulse (listed in Appendix A: Problem Space Exploration Data).

Built-in real-time error checking helps guide the missile creations. After creating a missile, data is exported to MFT to determine if the missile can be successfully launched and impact its target location. For interceptors, the data can be exported to IFT, which includes information such as "fan-out" diagrams that shows the available trajectories of the interceptor.

### b.	Missile Flight Tool (MFT)

MFT is used to model a missile's trajectory and export the trajectory file, including missile stage impact locations, to STK for further analysis. MFT can be used with preloaded generic ballistic missile models with varying ranges and performance characteristics or with imported missiles from MFT. Basic inputs such as launch and target locations, missile types and quantities, trajectory and launch timing can all be varied in MFT. Additionally, constant values such as minimum and maximum range can be shown. Each missile flight scenario was simulated in MFT. If the simulation showed the simulated missiles could launch and fly to their intended destination, the scenario was exported to STK for animation and further analysis.

Custom missiles were designed in MDT and exported to MFT for trajectory analysis. However, custom missiles often produced inconclusive or unexpected results and after consulting with the AGI technical support staff it was discovered that there could be possible coding errors in the software package. Those errors would be addressed in the next release of the software.

Whenever feasible, missiles were chosen from the generic missile library that most closely represented the performance characteristics of the threat missiles. When a threat missile did not have a generic missile equivalent, custom missiles were designed and used in the simulation.

### c.	Interceptor Flight Tool (IFT)

IFT models ballistic missile defense intercept capabilities. Given the trajectory of a threat missile and the geographical location of an interceptor battery, IFT analyzes and provides an engagement summary that can be exported to STK. The results of a given configuration are deterministic, meaning they have the same results each time. Those results are provided on a per-missile basis. The IFT files are saved in an XML format that can be imported into other software packages for further analysis. The cohort took advantage of the XML format to parse the IFT results with BASH shell (Free Software Foundation, Inc 2011) scripts as described in Chapter VI, Section F: Baseline

DAF Scenario Results. Engagements are determined based on the physical properties and performance of the components, such as: threat missiles, interceptors, geographical distances, etc. If IFT determined an intercept was physically possible, the analysis showed a successful engagement (intercept of a threat missile). The intercept result is provided as a deterministic, binary (True or False) result, not a probabilistic distribution. By dividing a defended area into a grid (DAF analysis) and evaluating the binary engagement results, the cohort was able to determine whether that area (the political borders of Turkey in this analysis) was protected. Additionally, by assigning a probability of intercept for each interceptor battery and evaluating the effects of multiple defensive layers, i.e., how many interceptor batteries were able to engage a threat, the cohort determined the probability of intercepting a specific threat missile.

The IFT modeling engine provides several intercept modeling scenarios, each with a wizard to guide the user through the requisite steps of setting up and running the scenario. The two methods used by the cohort to analyze the EBMD system were "One Versus Many" (1VM) and "Defended Area Footprint" (DAF). In each IFT scenario, the AN/TPY-2 radar was used for the radar sensor since it was deployed at the time and thus part of the Baseline system. The interceptors were set to fire as soon as a threat missile was detected by the radar sensor – the earliest time possible. For DAF scenarios, the cohort used a grid resolution of one degree in latitude by one degree in longitude.

(1) One Versus Many (1VM) Method. In a 1VM scenario, an interceptor battery and one or more threat missiles are defined for analysis. One or more sensors are also defined to detect those threat missiles. When the 1VM simulation is run, IFT calculates the trajectory of each missile and, based on user defined parameters defining when to engage, determines if an interceptor from the battery can successfully intercept that specific missile.

The 1VM scenario type is useful when a specific ballistic missile threat is known, e.g., when a particular missile type with specific launch and target locations is known. In this case, 1VM provides a relatively accurate and precise model of the situation since each of those parameters is defined. For testing threats to a general

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area, a 1VM test case requires setting up many individual missiles targeting that area and a DAF scenario type is more appropriate.

(2)   Defended Area Footprint (DAF) Method. In a DAF scenario, both an interceptor battery and a geographical region or footprint to defend are defined. After the footprint is defined, IFT generates a target grid for the footprint based on the launch location and range of the threat missiles and the level of grid resolution desired. Using a given interceptor battery, threat missile trajectories and target grid, IFT analyzes each grid point to see if an interceptor can successfully engage the missile targeting that point. When the simulation finishes, IFT exports the results to STK by coloring each square of the target grid. The exported grid is colored coded as red, yellow and green. Red and green grid squares are grid points that were indefensible or defensible by the interceptor battery, respectively. Yellow grid squares are areas that are not reachable by the threat missile due to minimum or maximum range constraints.

The DAF scenario is advantageous for modeling regional defense as IFT performs the work to test multiple missiles targeting an area. IFT only models a single missile per grid point area, however, so modeling a threat on a specific trajectory would not be precise.

D.   BASELINE SCENARIO MODELING

The cohort created scenarios in STK for both the Baseline and EBMD Alternative solutions, as described in the following sections. The Baseline scenarios represent the system currently deployed while the EBMD Alternatives were designed to cover capability gaps evident in the Baseline, as shown through M&S.

1.   Baseline System Model

The Baseline system represented defense systems deployed in the Turkey region at the time of the analysis. The Baseline system consisted of one AN/TPY-2 tracking radar system, six Patriot Advance Capability (PAC-3) interceptor batteries, and two Aegis BMD-capable ships in the Mediterranean Sea (O'Reilly 2011, 6). A series of threat scenarios were generated to represent current threat capabilities and to stress the Baseline

system in the model to determine its capabilities and limitations and to evaluate the initial assumptions used in generation of the model. Five threat scenarios used in a 1VM analysis of the Baseline system are provided below and summarized in Table 19 and detailed in Table 20.

In all threat scenarios, the ballistic missile threats were launched from the Tabriz Missile Base in northwestern Iran. The two ballistic missile threat types used in the scenarios are the Shahab-3 and the Sejil-2. The Shahab-3 is an MRBM with an approximate range of 1280 km (Federation of American Scientists 2008) and the Sejil-2 is an IRBM with a speculated range of more than 2000 km (George C. Marshall and Claremont Institutes 2013c).

Threat Scenario	Description
1	Launch of one Shahab-3 missile from the Tabriz Missile Base in northwestern Iran with a target of Kürecik, Turkey, where the AN/TPY-2 radar is stationed.
2	Launch of two Shahab-3 missiles with a target of Kürecik, Turkey with a delay of 60 seconds between launches.
3	The simultaneous launches of two Shahab-3 missiles with a target of Kürecik, Turkey.
4	Launch of ten Shahab-3 missiles. The missiles are launched sequentially with a delay of 60s between launches. Every other missile is targeted towards Kürecik, Turkey, with the other five missiles targeted at Incirlik Air Base in Incirlik, Turkey.
5	Launch of one Shahab-3 missile with a target of Kürecik, Turkey; one simultaneous launch of a Sejil-2 missile with a target of Ankara, Turkey; and one additional Sejil-2 missile with a target of Istanbul, Turkey.

Table 19.   Baseline IVM Threat Scenarios High Level Summary

Threat Scenario	Missile No.	Launch Timing (sec)	Missile Type	Target Location
1	1	Initial	Shahab-3	Kürecik
2	1	Initial	Shahab-3	Kürecik
	2	T+60	Shahab-3	Kürecik
3	1	Initial	Shahab-3	Kürecik
	2	Initial	Shahab-3	Kürecik
4	1	Initial	Shahab-3	Kürecik
	2	T+60	Shahab-3	Incirlik
	3	T+120	Shahab-3	Kürecik
	4	T+180	Shahab-3	Incirlik
	5	T+240	Shahab-3	Kürecik
	6	T+300	Shahab-3	Incirlik
	7	T+360	Shahab-3	Kürecik
	8	T+420	Shahab-3	Incirlik
	9	T+480	Shahab-3	Kürecik
	10	T+540	Shahab-3	Incirlik
5	1	Initial	Shahab-3	Kürecik
	2	Initial	Sejil	Ankara
	3	Initial	Sejil	Istanbul

Table 20.   Baseline IVM Threat Scenarios Detailed Summary

2.   STK Objects

Although STK supports many types of objects, only the following STK specific object types were used to model the EBMD system: area targets, facilities, sensors, ships, and missiles or interceptors with their major components. Basic missile objects and trajectories were provided with STK natively; however, the MMT plug-in provided increased customization and flexibility for missiles and interceptors. MMT's added usability proved necessary to evaluate the performance of specific threat missiles and interceptors. Generic missiles provided with MMT and some custom designed missiles from MDT were used in the model.

a.   Area Targets

Area targets are geographical areas defined and displayed in the STK scenario map. The area targets can be custom defined with latitude and longitude coordinates, but pre-defined areas, such as country borders, can also be selected from the

comprehensive STK database. Despite having the word "target" in the object type name, these objects are useful to show a country's borders even when not used as a target. Consequently, the countries of Turkey, Syria, and Iran were defined as area targets and outlined in STK. The definition of Turkey as an area was necessary for performing DAF analyses in IFT; Iran and Syria were defined to provide context for the region.

b.   Facilities

Facilities are general objects that may represent a building, a compound, a city, or any type of facility. STK can define a facility as a specific city through its built-in city database, though facilities may also be defined manually through latitude, longitude, and other measures including elevation, population, and political region. Facilities also support the association of certain other objects. For instance, a sensor object can be assigned to a facility, correlating its placement and usage.

For this project, specific cities, missile bases and radar stations were defined as facilities. The majority of the cities were available in the built-in database; the remaining cities were manually defined by longitude and latitude. Facilities were established at Tabriz, Iran; Kürecik, Turkey; and Incirlik, Turkey to represent the missile launch site and targets, respectively, with Kürecik also being a radar station.

c.   Sensors

A sensor detects other objects or activities. For this project, radar systems were represented by sensors and were assigned to facilities and ships as appropriate, to detect objects within a defined field of view. Lateral and vertical ranges and azimuth angle were defined for each sensor to represent existing radar systems.

A sensor object representing the AN/TPY2 phased-array radar at the Kürecik facility was defined with a 120 degree aperture and a range of 1000 km (Defense Industry Daily 2013b). The sensor was set to point towards Iran and scan from 11° to 131° in the azimuth angle to cover Western Iran, Syria and the Eastern end of Turkey. This is displayed in Figure 26 as the large magenta-colored grid in the right half of the picture.

Figure 26 was produced using the STK software by AGI (Analytical Graphics Incorporated 2013).

A sensor was attached to each Aegis-BMD ship representing the AN/SPY-1D radar system, providing 360° coverage with a detection range of 550 km (Lewis and Postol 2012a). These sensors are displayed in Figure 26 as the purple hemispheres surrounding each Aegis ship.

Each PAC battery included a sensor representing a 360 degree AN/MPQ-65 radar system with a range of 170km (Army Recognition 2013).

d. Ships

Ships are objects similar to facilities that are placed in marine areas. Ships can travel between a defined set of waypoints. Like a facility, sensors can be assigned to ships, as can missiles and an array of other objects. As an example, each Aegis ship in the project's scenarios is assigned a sensor representing the AN/SPY-1D radar system as mentioned earlier.

e. Missiles and Interceptors

Missiles are a unique object type in STK that are associated with a trajectory including launch data, apogee, and target.

Interceptors are missile objects as well and recognized separately in IFT in order to distinguish between ballistic missile threats and the missiles used to intercept them. MFT and IFT automatically calculate and export all trajectory information to STK based on the missile's characteristics like mass and propulsion. Various missile stages and their individual trajectories are also exported.

The cohort used generic missile and interceptor models provided with MMT (when they approximated the characteristics of real missiles) as well as custom missiles designed in MDT. Missiles were "flown" in MFT and then exported into STK. Interceptors were modeled first in IFT and then exported to STK. Although missiles are natively supported in STK, the MMT add-on tools enhance usability by automatically

generating the missiles' trajectories and calculating when an interceptor can successfully engage a ballistic missile threat.
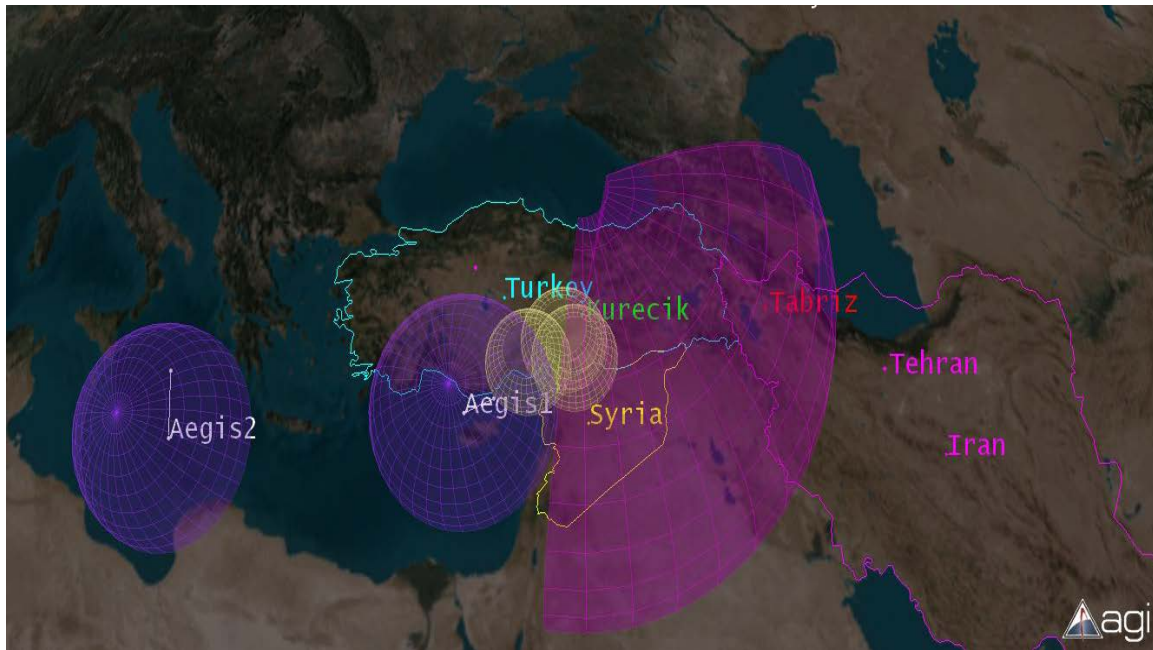
Figure 26.   Baseline Objects

3.   Launch Locations

As described in Chapter VI, Section D: Baseline Scenario Modeling, launch locations were based on known, or suspected, sites in Iran that possessed the missile capabilities to launch a Shahab-3 and Sejil-2 type missiles. The possible launch locations considered for modeling were taken from The Nuclear Threat Initiative (The Nuclear Threat Initiative 2011a; The Nuclear Threat Initiative 2011b; The Nuclear Threat Initiative 2013). Those locations of possible launch sites are provided in Table 21. The Tabriz Missile Base was chosen for modeling because of its close geographical proximity to Turkey. Tabriz's closer proximity makes it the highest threat since missiles launched there can reach more destinations in Turkey.

Launch Location	City	Coordinates	Usage
Tabriz Missile Base	Tabriz	38.0833° N, 46.2833° E	Silo Launcher
Imam Ali Missile Base	Khorramabad	33.4667° N, 48.3500° E	Silo Launcher
Qom Space Center	Qom	34.65000°N 50.90000°E	Space Testing
Emamshahr Space Center	Shahrud	36.42000°N 55.02000°E	Space Testing
Semnan Missile Complex	Semnan	36.00000°N 54.00000°E	Usage

Table 21.   Launch Locations

4.   Target Locations

Target locations for IVM scenarios were divided into two categories: populated cities and military installations. Target locations were further refined to only include those located within range of the threat missiles from a launch facility located at Tabriz, Iran. Populated cities were limited to cities with greater than 300,000 people. The target locations were then sorted by distance from the Tabriz Missile Base. Target locations that were used in M&S are shown in Table 22. Target locations were established at Incirlik, Kürecik, Ankara and Istanbul, with the AN/TPY-2 radar in Kürecik being a critical target location because of the radar facility. A complete list of target locations considered for M&S are provided in Appendix A: Problem Space Exploration Data.

City	Distance From Tabriz (km)	Coordinates
Incirlik	470	37.0019° N, 35.4258° E
Kürecik	750	38.0667° N, 38.0167° E
Ankara	1178	39.9272° N, 32.8644° E
Istanbul	1518	41.0408° N, 28.9861° E

Table 22.   Modeling And Simulation Target Locations For 1VM Scenarios

5.   Interceptor Batteries

Batteries of interceptors were placed at various locations to model what was already deployed or to find the places of maximum coverage from the battery. Three types of batteries were used in the MMT modeling effort: PAC-3, SM-3, and THAAD.

a. *Patriot Advanced Capacity 3 (PAC-3)*

Three PAC-3 interceptor batteries were placed in southern Turkey at Adana, Gaziantep, and Kahramanmaras, owned by the NATO contingents of the U.S., the Netherlands, and Germany, respectively (North Atlantic Treaty Organization 2013). Although at the time of the modeling there were two PAC-3 batteries deployed to each of these three locations (for a total of six PAC-3 batteries) the redundancy of the batteries had no effect in the model and, for the sake of simplicity, only one battery was defined per location. PAC-3 batteries are truck-based and use the MIM-104 Patriot M901 launch station, each holding 16 interceptors (IHS Janes 2013).

b. *Aegis-based Standard Missile 3 (SM-3)*

The Aegis missile defense system consists of detection and tracking radar, information processing, and missile interceptor components (IHS Jane's website, under "AEGIS weapon system MK-7," 2001, accessed 2013). As of November, 2012, Aegis had been integrated onto 26 Navy cruisers or destroyers (Missile Defense Agency 2013c) with future plans for a ground-based "Aegis Ashore" system. These Aegis BMD systems use the SM-3 interceptor with capacities up to 128 interceptors, configured in groups of eight (DDC-I 2013).

The ships used in the STK model were given a starting position and a simple straight line route to patrol. Representing the Aegis-BMD ships, one ship was positioned in the Northeastern Mediterranean, North of Cyprus, and the second Aegis ship was placed outside the area of engagement in the central Mediterranean. The second Aegis-BMD ship was initially placed outside of the range of engagement given the cohort's assumption it would be patrolling or performing other non-BMD functions elsewhere in the Mediterranean Sea. This assumption arose due to the fact only two Aegis-BMD ships were deployed for the entire Mediterranean Sea and would not be congregated in a single location.

c.   *Terminal High Altitude Area Defense (THAAD)*

The THAAD system consists of a mobile command station and interceptor batteries. THAAD uses the AN/TPY-2 radar for detection and tracking. THAAD interceptor batteries are truck-mounted and each vehicle has a capacity of ten interceptors (Encyclopedia Astronautica website, under "THAAD," 2011, accessed 2013). THAAD offers higher mobility and a much larger intercept range than PAC-3. The THAAD interceptor has a maximum range of 200 km (Encyclopedia Astronautica 2011) whereas the MIM-104F (the PAC-3 interceptor) has a maximum range of 15 km (IHS Janes 2013).

6.   Interceptors

The interceptor used by the Aegis missile defense system is the SM-3. The modeling used the Block 1A version of the SM-3 with a payload mass of 23 kg and horizontal range of 1200 km (IHS Jane's website, under "Standard Missile 1/2/3/5/6 (RIM-66/67/156/161/165/174)," 2012, accessed 2013). A conflict was encountered regarding the range of the SM-3. As cited earlier in this paragraph, the cohort consulted IHS Janes to obtain range of 1200 km; however, numerous other sources were found that provided a range between 500 km (Encyclopedia Astronautic website, under "Standard SM-3," 2011, accessed 2013) and 600 km (Guide to Military Equipment and Civil Aviation website, under "Standard SM-3 Block IA," 2013). The cohort used the IHS Janes reference.

The cohort created a custom interceptor in MDT that approximated the same specifications; however, the results in IFT were inconsistent when simulated. To ensure consistent results, the cohort instead used IFT's generic medium-range interceptor (MRI_1–1100) with a payload mass of 65 kg and maximum horizontal range of 1100 km to represent the SM-3 Block 1A. The PAC-3 interceptors, which have a reported range of 15 km (IHS Janes 2013) were represented by the SRI_1–20 generic interceptor in IFT with a horizontal range of 20 km (Federation of American Scientists website, under "Patriot TMD," 2000b, accessed 2013). Initial experimentation with the PAC-3

interceptor showed its limited range severely restricted its effectiveness in the model to intercept the threat missiles. As a result, the cohort included the PAC-3 in modeling the Baseline system, but did not use the PAC-3 when modeling EBMD Alternatives. .

7.   Threat Missiles

Two threat missiles, the Shahab-3 and Sejil-2, were exported from MFT and MDT to STK, respectively. To represent the Shahab-3 missile the generic short-range missile 3 (SRM-3) with a similar range of 200 km (min)-1500 km (max) (Federation of American Scientists 2008) was used. A custom missile was created to represent the Sejil-2 since no generic missile had similar performance characteristics. A two-stage missile with a range of 290 km (min)–2,300 km (max) (George C. Marshall and Claremont Institutes 2013c) was modeled to represent the Sejil-2. The detailed characteristics of the two threat missiles modeled are provided in Table 23 (George C. Marshall and Claremont Institutes 2013b; George C. Marshall and Claremont Institutes 2013c). Selection of these missiles was based on their operational status and ability to strike key cities in Turkey.

Name	Shahab-3	Sejjil-2
Class	MRBM	IRBM
Range (km)	1,280	2,000 - 2,500
Payload (kg)	760 - 1,158	650 - 1,000
Stages	1	2
Propellant	Liquid	Solid
Speed (km/s)	2.0–2.4	Unknown
Height (m)	15.5	17.6
Width (m)	1.25	1.25

Table 23.   Operational Threat Missile Characteristics (After George C. Marshall and Claremont Institutes 2013b; George C. Marshall and Claremont Institutes 2013c)

8.   IFT Parameters

IFT allows configuration of numerous parameters to define the model; these parameters differ somewhat depending on the type of scenario being modeled (1VM, DAF, etc.). The parameters include the type and launch location of an interceptor battery;

the target, along with its launch location and type; and various delays between when a target is detected by a sensor and when and interceptor can launch. The IFT parameters modified for this project are listed in Table 24.

Parameter	Example	Explanation
Battery interceptor type and location	SM-3 on Aegis1	An interceptor battery is defined by specifying an interceptor type from a list of those built in to IFT or imported from MDT. The location of the battery can be custom defined or selected from a list of objects automatically imported from STK.
Battle management delay time (battle delay)	10 seconds	This is the time in seconds between the sensor detecting a missile and the interceptor battery launching an interceptor.
Target launch location (DAF ONLY)	Tabriz	This can be defined with custom coordinates or selected from a list of objects defined in STK. It represents where the target missile is launched, which determines which grid points it can hit.
Target impact (DAF ONLY)	STK/Area Target Boundary Grid	This parameter defines what type of footprint is defended – whether a custom-defined square or a political boundary, etc. The STK/Area target can be selected from a list of areas defined in STK.
Grid density	1, 1	These numbers represent the number of degrees latitude and longitude included in each grid point. Larger numbers mean larger (coarser) grid points.
Target type (DAF ONLY)	SRM_3	The target type is the type of threat missile used to generate the grid points the interceptors must defend against. The target type is selected from a list of missiles known to MFT: either built-in or imported from MDT. The missile type will determine minimum and maximum range which determines which grid points can be hit.
Targets (IVM) or Target Grids (DAF)	Shahab_1_l2i	IFT presents the user with a list of possible targets imported from STK.

Parameter	Example	Explanation
Sensors	Kürecik / AN_TPY2	IFT allows the user to select one or more sensors from a list of sensors that have been defined in STK. The sensor will be shown with the location it is associated with in STK.
Sensor requirements	Any one detection prior to launch	The user can select whether an interceptor can be launched as soon as a target is detected by any sensor, if it needs to be covered by sensors at time of launch or if multiple sensors are required for tracking before launch. The battle management delay is in addition to this potential delay.
Engagement window	Earliest Time	This parameter tells the modeling engine when to attempt to incept the target. Options include: earliest time, latest time, maximum altitude and minimum altitude.

Table 24.   IFT Parameters

E.   BASELINE 1VM SCENARIO RESULTS

This section contains the results of the IFT simulations of the five Baseline scenarios as listed in Table 19 and Table 20. These scenarios are "1VM" scenarios where one interceptor battery defends against one or more threat missiles. The scenario results are shown in Table 25. The percentage of the targets intercepted varies with changes in the battle delay; longer battle delays may prevent an interceptor from reaching the incoming threat missile before it hits its target. As mentioned in Chapter VI, Section D: Baseline Scenario Modeling, there were actually two Aegis ships deployed in the Mediterranean Sea; however, because only one ship would be in the vicinity of Turkey in a typical patrol, only one ship was used in each Baseline scenario, as shown in Table 25.

According to a conversation with Professor John Green (in 2013) of the NPS Systems Engineering department, a typical battle delay (per the previous section, the time between threat detection and interceptor launch) for an interceptor would range between 8–20 seconds, with 4–8 seconds to process the threat, 2–4 seconds to transmit the data from the radar to the interceptor controller, and 4–8 seconds to ready the missile. The

apparent battle delay time is reduced somewhat from the sum of these numbers by performing some of the tasks in parallel.

PAC-3 batteries were tested in the original Baseline scenario, but their short range of 15 km prevented any successful intercepts since the Shahab-3 and Sejil-2 missiles fly as high as 200 km as modeled in MFT. Due to their inability to defend against the threats, they are not included in the results for the Baseline or EBMD Alternative scenarios.

Threat Scenario	Shahab-3 Missiles	Sejil-2 Missiles	Aegis Ships	Battle Delay		Percent Intercepted (%) at Battle Delay (s)	
				Min	Max	% Hit	Delay (s)
1	1	0	1	8	14	100	8
						0	9
2	2	0	1	8	9	100	8
						0	9
3	2	0	1	8	9	100	8
						0	9
4	10	0	1	4	16	100	4
						80	6
						60	8
						40	10–16
5	1	2	1	8	16	100	8
						66	9–16

Table 25.   Summary Results of the Baseline System for 1VM Scenarios

1.   Scenario 1

In the first scenario, a battery of SM-3 missiles aboard an Aegis ship in the Mediterranean Sea defended against a single Shahab-3 missile from Tabriz, Iran targeting Kürecik, Turkey. The significance of Kürecik as a target is the powerful AN/TPY-2 tracking radar system deployed there that a hostile force would want to disable.

To test the scenario, the interceptor battle delay was varied between eight and sixteen seconds; battle delay times beyond sixteen seconds did not make a difference in the results and are thus not displayed. An eight second battle delay signifies near-ideal times to process and transmit threat data to the interceptor battery and prepare the

interceptor for launch. While eight seconds is an optimistic battle delay, it provides important capability data given the position of the ship. As shown in Table 25, a battle delay of more than eight seconds results in the inability to defend against the threat missile. A delay of eight seconds or less results in a successful engagement. Were the Aegis ship closer, a longer battle delay could be used while maintaining a successful engagement, signifying the missile threat was neutralized.

A picture of Scenario 1 is shown in Figure 27, produced using the STK software by AGI. This picture shows the coverage of the AN/TPY-2 radar system in magenta. Each Aegis ship is depicted inside the blue radar dome produced by the AN/SPY-1D radar onboard the ships. A white trajectory above the yellow arrow on the right is the Shahab-3 missile fired from Tabriz. The light blue trajectory pointed to by the yellow arrow on the left is the SM-3 interceptor's flight path en route to intercepting the Shahab-3. In all cases, the threat missile is detected first and tracked by the AN/TPY-2 radar. That tracking information is sent through the BCN to the Aegis ships, allowing launch of an interceptor.
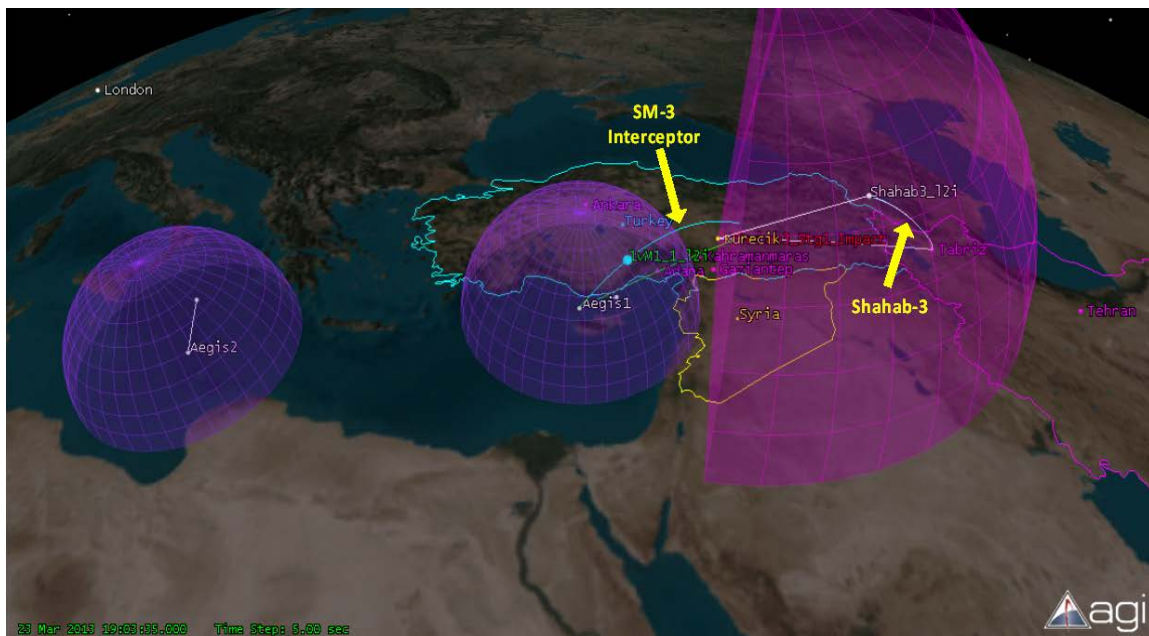
Figure 27.   Scenario 1. Aegis SM-3 Battery Defending against Shahab-3 Missile

2.   Scenario 2

Scenario 2 is similar to the first scenario in that Shahab-3 missiles were launched from Tabriz, Iran towards Kürecik, Turkey. Scenario 2 differs in that two missiles were launched instead of one, with a sixty second delay between launches. Because an Aegis SM-3 battery can hold dozens of SM-3 interceptors (DDC-I 2013), multiple missile interceptions are not a problem as long as the target missiles are in range with enough time for each interceptor to travel to an intercept point with the incoming threat missile after waiting the mandated battle delay. Per the IFT results, these missiles were in range (time and distance) as long as the battle delay was less than or equal to eight seconds, just as in Scenario 1. When the battle delay was greater than eight seconds, the intercept was unsuccessful.

3.   Scenario 3

Scenario 3 also consists of two Shahab-3 missiles fired from Tabriz, but differs in that the missiles were launched simultaneously instead of with a sixty second delay. As in Scenario 2, a successful engagement of all missiles is possible as long as they are within range. All engagements failed when the battle delay was greater than eight seconds, while they were successful with a battle delay of eight or fewer seconds.

4.   Scenario 4

Scenario 4 is more complicated than the other scenarios and represents a large salvo of threat missiles. This scenario models the capability to intercept multiple threat missiles on different trajectories. Five missiles are launched from Tabriz, Iran to Kürecik, Turkey and another five are launched towards Incirlik Air Base. The missiles are staggered both in their launch times and destinations. The first threat missile targets Kürecik. The second launches sixty seconds later and targets Incirlik. The third launches sixty seconds after the second and targets Kürecik, and so on.

Unlike the previous scenarios, the Aegis SM-3 battery had a more difficult time hitting all the targets with an eight second battle delay. As shown in Table 25, the battle delay would have to be reduced to an unrealistic four seconds in order to intercept 100%

of the missiles. Only six of the ten missiles were hit when incorporating an eight second battle delay; with a delay of ten to sixteen seconds, four missiles were hit (all targeting Incirlik).

5.   Scenario 5

This scenario differs from the first four scenarios by including the medium-range ballistic missile: the Sejil-2. Whereas the Shahab-3 is a single-stage short-range missile, the Sejil-2 has two stages, allowing it to reach over 2,000 km (George C. Marshall and Claremont Institutes 2013c). This range allows Iran to target Western Turkey, including the key metropolis of Istanbul. This scenario demonstrates defensibility against multiple missile types and across most of Turkey.

With the single Aegis ship engaging the threat missiles as in the previous scenarios, the interceptors were able to successfully engage the threat 100% of the time when the battle delay was eight seconds or less. When the delay was increased to between nine and sixteen seconds, only two of the threat missiles were intercepted (a 66% intercept rate). The two threat missiles that were intercepted were the Sejil-2, which was due to the time of flight being much

6.   Summary of Baseline One-Versus-Many Simulation

The Baseline scenarios show that the battle delay and target location is critical to defending against incoming threat missiles from Tabriz to Kürecik. The Baseline 1VM scenario results assisted in determining the existing system limitations (Research Question 4). An Aegis ship north of Cyprus must have a battle delay of eight or fewer seconds to defend Kürecik, Turkey and that number may very well be unrealistic when factoring in the time it takes to transmit tracking data from the AN/TPY-2 radar to a ship-based Aegis interceptor battery. Positioning the Aegis ship as close to the target (Kürecik in this case) allows for a longer battle delay. However, it is not financially practical to station a sophisticated Aegis warship in a relatively stationary position to defend a small target al.so, as demonstrated in Scenario 4 with the missiles targeting Incirlik Air Base, those targets closest to the Aegis ship are more easily defended.

F.   BASELINE DAF SCENARIO RESULTS

A DAF analysis was performed on the Baseline scenario with each missile type to determine the ability to defend Turkey. The 1VM model simulated the ability to intercept specific threat missiles, whereas the DAF scenarios simulated whether an entire region was defensible.

To perform a DAF analysis, a target grid was established. The political border of Turkey was defined as the perimeter of the area to be defended. A target grid was generated with a latitude/longitude resolution of one-degree (The finest resolution the software was capable of) and bounded by the Turkey's borders. Due to limitations in IFT, only one interceptor battery location and missile type could be chosen for each analysis. To compensate for that limitation, multiple interceptor batteries and threat missile types were saved in the same IFT file and run as individual simulations. Additional parameters for each DAF analysis were defined such as battle management delay, sensor requirements, engagement window and export options. The battle management delay was varied between 8 and 14 seconds for incoming threat missiles. Sensor requirements were defined by choosing available sensors from the linked STK scenario file, and the number of sensors required to acquire tracking data before launching an interceptor. The AN/TPY-2 sensor was chosen for each DAF analysis and the engagement window was set to the earliest time possible in the threat missile trajectory.

After defining the interceptor, target grid and evaluation options, the DAF analysis was performed. The results of the DAF analysis were exported to STK for viewing. The DAF grid that is exported to STK is color-coded as red, yellow and green. Red and green grids are areas that were indefensible or defensible by the interceptor battery, respectively. Yellow grids are areas that are not reachable by the incoming threat missile. A DAF analysis was performed for each threat missile type and different interceptor battery locations.

1.   Sejil-2 DAF

The Sejil-2 DAF for the Baseline scenario is shown in Figure 28 produced using the STK software by AGI. The grid in Eastern Turkey is yellow as those points are less than the Sejil-2's minimum range and therefore unreachable. Grid points in Western Turkey are green and are defensible by the Aegis-BMD ship north of Cyprus. Central Turkey, however, is largely red, signifying failure to intercept the threat missiles targeting those grid points. Red grid points can stem from two possibilities. Either the interceptor does not have the range to reach the grid point, or the interceptor cannot reach the grid point before the incoming threat missile impacts the target. The time to intercept is a function of the sensor detection time, battle management delay and the time of flight of the interceptor.
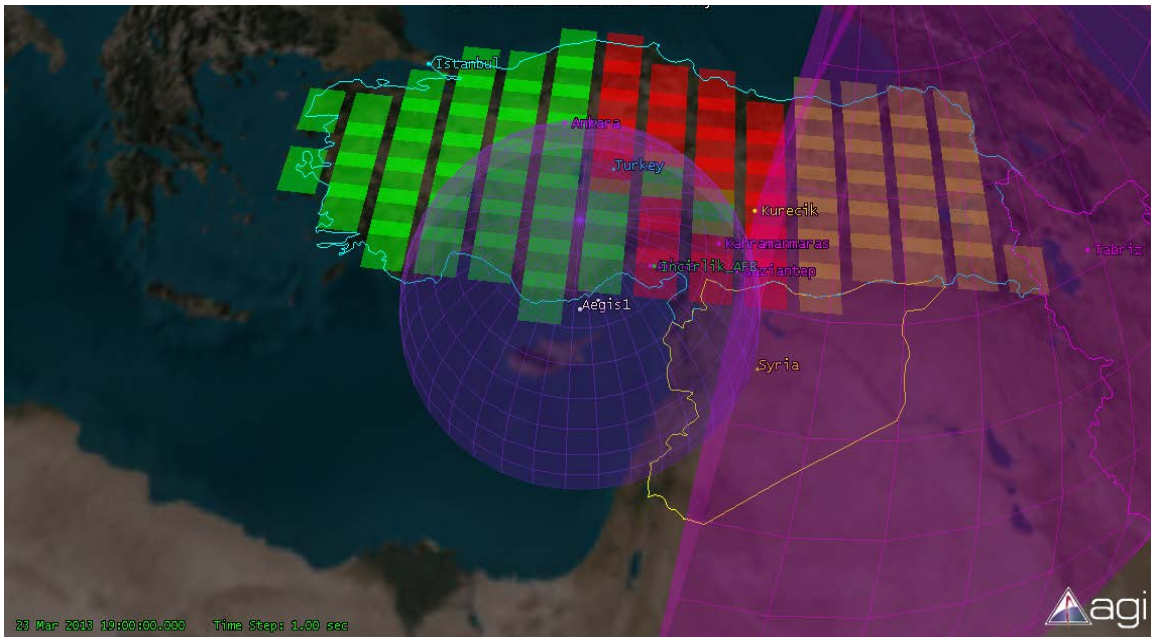
Figure 28.   Sejil-2 DAF Results

Using the DAF grid output, the percentage of the high-value footprint defended (P_{fd}) was determined by dividing the number of defensible (green) grid points ($N_{Defended}$) by the total number of grid points that were defensible (green) and indefensible (red) ($N_{Undefended}$) as shown in Equation 1.2.

$$(1.2) \qquad \frac{N_{Defended}}{N_{Defended} + N_{Undefended}} = P_{fd}$$

The percentage of area defended for this DAF scenario was 63.5%.

2.   Shahab-3 DAF

A DAF analysis of the Baseline scenario with a Shahab-3 threat missile was also performed and the grid output is shown in Figure 29 produced using the STK software by AGI. The defensible and indefensible areas are different than the Sejil-2 DAF due to the performance capability of the Shahab-3 threat missile. Grid points in Western Turkey are unreachable by the Shahab-3. Eastern Turkey is largely indefensible because the interceptor cannot reach that area before the Shahab-3 impacts the target grid point. The percent footprint defended for the Shahab-3 DAF analysis was 65.8%.
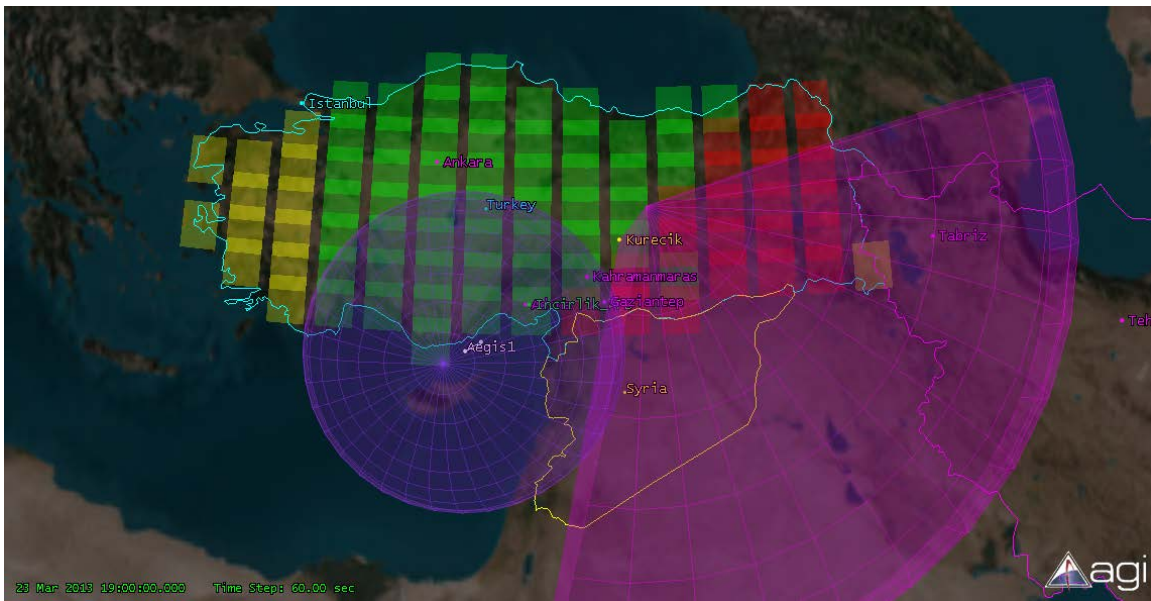
Figure 29.   Shahab-3 DAF Results

3.   DAF Comparison

The individual DAF output results that were saved in the IFT file were combined and analyzed with custom scripts to determine the defensive capability against multiple

threat missile types. This was also performed during alternative analysis to simulate using multiple interceptor batteries against multiple threat missile types. The scripts were written in BASH and provided data on the percentage of the grid covered by one or more interceptor batteries and how many levels of protection a grid point had (Free Software Foundation, Inc., website, "Bash Reference Manual," 2011). The scripts are shown in Appendix C: Modeling And Simulation Script Details.

To analyze the Baseline system against multiple missile types, two DAF analyses were combined and analyzed. Each DAF analysis exported a summary result for each grid point. The DAF analyses were combined, sorted and filtered to determine at each result point if the threat missile was intercepted (defensible). This filtering was also used for multiple systems and missile types to determine if two systems can defend the same grid point.

4. Summary of Baseline DAF Scenario Results

A summary of the DAF analysis for the Baseline system against each missile type is provided in Table 26. The combined output of multiple threat missile types was determined by counting all of the unique result points between the Sejil-2 and Shahab-3 DAF analyses for the Baseline system. The total percent footprint defended (P_{fd}) by the Baseline system against the Sejil-2 and Shahab-3 threat missile types was 70.1%. The probability of intercept (P_i) was calculated for the defended area footprint by multiplying each grid point by the probability of intercept, at that grid point, and then averaged over the entire footprint. For one system, the probability of intercept was 0.713 (taken from Chapter VI, Section B: Determining the Probability of Intercept). If the grid point could not be defended, the probability was zero. The probability of intercept was assumed to be the same for each type of interceptor. For the total percent footprint defended, the probability of intercept for the footprint was calculated for each threat missile type and as a single overall value. The percent footprint defended with the Baseline components was 61.4%. The combined results are also represented visually as shown in Figure 30.

Threat Missile Type	Total Grid Points	Total Defended Grid Points	Total Missed Grid Points	Percent Footprint Defended P_{fd}	Probability of Intercept (P_i)
Sejil-2	63	40	23	63.5%	0.635
Shahab-3	76	50	26	65.8%	0.587
Combined	87	61	26	70.1%	0.614

Table 26.　　　Baseline DAF Results Summary

Figure 30.　　　Combined Defense Layers for Baseline against Sejil-2 and Shahab-3

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VII. ALTERNATIVES REFINEMENT

A. ALTERNATIVES REFINEMENT PROCESS

The general approaches to alternatives, defined in Alternatives Generation (Chapter V), were refined during the alternatives refinement process (Figure 31). Each approach was simulated and the resulting performance of those EBMD Alternatives was recorded using evaluation measures from the requirements analysis process. The evaluation measures of each EBMD Alternative were used to inform the analysis of alternatives.
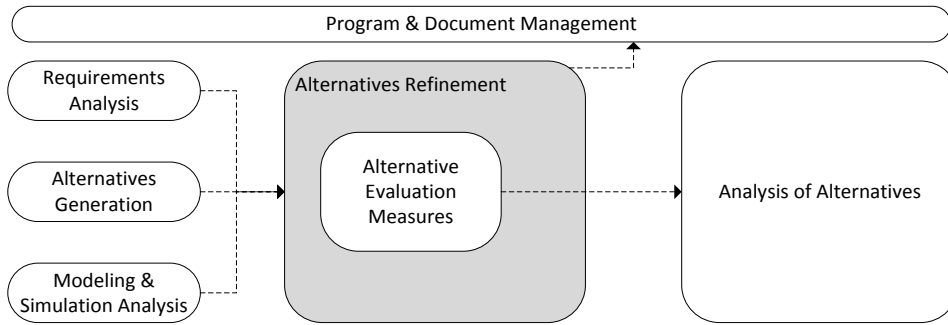
Figure 31.   Alternatives Refinement Process

B. A NEED FOR NEW ALTERNATIVES

The Baseline system represented defense systems deployed in the Turkey region at the time of the analysis. Based on the results of the 1VM and DAF analyses, performance gaps were identified, illustrating the need for alternative systems. Specific EBMD Alternatives were derived from general guidance provided during the alternatives generation process. The goal of M&S was to take the general guidance provided for each alternative and iteratively add, move and remove components in each alternative based on the performance results of each iteration. This iterative process continued until the addition or movement of additional systems did not result in a significant performance increase over the previous iteration or the system achieved full coverage of the high value area. A summary of the quantities of components used for each alternative is provided in

Table 27. For example, the general approach for Alternative B was to alter the quantity and location of THAAD batteries. Alternatives B.1 through B.3 correspond to the number of THHAD batteries used in the simulation where Alternative B.1 corresponded to one THAAD battery.

| Alternative | Component | | | | |
	AN/TPY-2 Radar	Aegis Ships	THAAD Batteries	PAC-3	Aegis Ashore
Baseline	1	1	0	6	0
A	1	2	0	0	0
B.1	1	2	1	0	0
B.2	1	2	2	0	0
B.3	1	2	3	0	0
C	1	0	0	0	1

Table 27.   Component List for Alternative Analysis

C.   PERFORMANCE COMPARISON

A DAF analysis was performed for each EBMD Alternative to assess its ability to defend the high-value footprint against the Sejil-2 and Shahab-3 missile types. Primary performance measures used were percent footprint defended (P_{fd}) and probability of intercept (P_i) for the total area defended.

When multiple systems were present and could defend the same grid point, then the number of layers for that grid point was increased to represent layers of coverage. The probability of intercept for the total defended footprint was calculated by multiplying each coordinate's number of defense layers by the corresponding probability of intercept for the respective number of defense layers and performing a weighted average of each grid point's probability of intercept over the entire area. The probability of intercept by number of defense layers is provided in Chapter VI. Section B: Determining the Probability of Intercept. The probability of intercept was assumed to be the same between different interceptor types. For example, assume that a particular system had no coverage of 21 grid points, one layer of coverage for 10 grid points and two layers of coverage for

57 grid points, for a total of 88 grid points analyzed. The probability of intercept would be calculated as shown in Equation 1.3.

$$P_i = \frac{\left(N_0 \times P_{zeroLayer}\right) + \left(N_1 \times P_{oneLayer}\right) + \left(N_2 \times P_{twoLayers}\right)}{N_{total}}$$

(1.3)

$$P_i = \frac{\left(21 \times 0\right) + \left(10 \times 0.713\right) + \left(57 \times 0.918\right)}{88} = 0.676$$

D. EBMD ALTERNATIVE SYSTEMS PERFORMANCE RESULTS

1. Alternative A

The general approach to Alternative A was to vary the number and placement of Aegis ships. For Alternative A, two Aegis ships were used in the simulation, whereas the Baseline had one active Aegis ship performing BMD. One Aegis ship was set in the same location as the Baseline system (35.6° N, 32.5° E) while the other was placed north of Turkey in the Black Sea (41.5° N, 38.1° E). Each Aegis ship was simulated to defend against the same missile types and set of grid points. The combined performance is summarized in Table 28 and shown in Figure 32.

Parameter	Result
Total Grid Points	88
Total Defended Grid Points	67
Total Missed Grid Points	21
Total Grid Points with Two Layers	57
Total Grid Points with One Layer	10
Total Percent Footprint Defended (P_{fd})	76.1%
Probability of Intercept (P_i)	0.676

Table 28.   Alternative A DAF Performance Summary

Figure 32.   Alternative A DAF Coverage

2.   Alternative B

To determine its effectiveness on overall coverage, between one and three THAAD batteries were added to Alternative A and designated as Alternative B.1, B.2 and B.3 corresponding to the number of THAAD interceptor batteries. Depending on the number of THAAD batteries, the position of each THAAD battery was changed to increase the defended area footprint. The positions of the THAAD batteries for Alternative B are provided in Table 29.

Alternative	THAAD Batteries	Location
B.1	1	39.347° N, 41.4° E
B.2	1	39.25°N, 42.4°E
	2	38.0°N, 39.2°E
B.3	1	40.211°N, 41.4°E
	2	38.222°N, 41.4°E
	3	37.0°N, 37.9°E

Table 29.   Alternative B THAAD Battery Locations

The performance summary for Alternative B is provided in Table 30 and shown in Figure 33, Figure 34, and Figure 35.

Parameter	Alternative		
	B.1	B.2	B.3
Total Grid Points	88	88	88
Total Defended Grid Points	79	85	88
Total Missed Grid Points	9	3	0
Total Grid Points with Four Layers	0	0	14
Total Grid Points with Three Layers	0	8	32
Total Grid Points with Two Layers	60	67	22
Total Grid Points with One Layer	19	10	20
Total Percent Footprint Defended (P_{fd})	89.8%	96.6%	100.0%
Probability of Intercept (P_i)	0.780	0.869	0.905

Table 30. Alternative B DAF Performance Summary

Figure 33. Alternative B.1 DAF Coverage
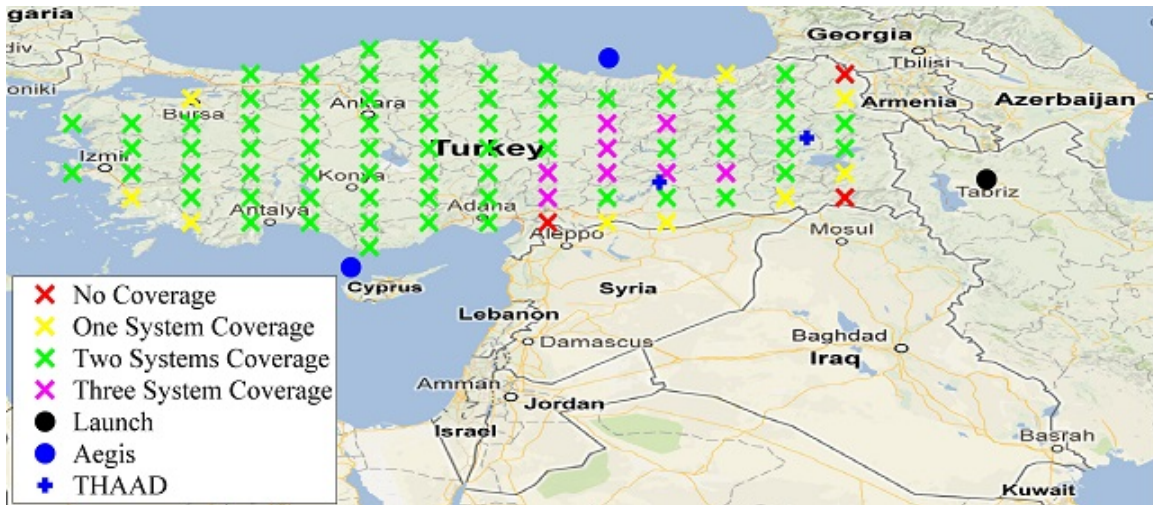
Figure 34.   Alternative B.2 DAF Coverage
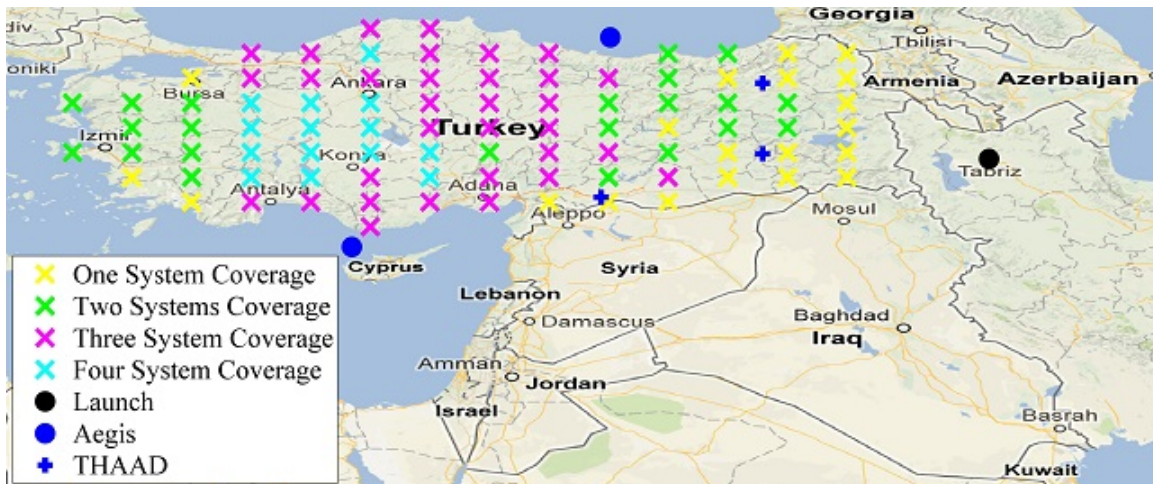
Figure 35.   Alternative B.3 DAF Coverage

3.   Alternative C

An Aegis Ashore system using the same interceptors as the Aegis ships used in the simulation was placed in Eastern Turkey (38.35°N, 41.3°E). A summary of the DAF performance for Alternative C is provided in Table 31 and shown in Figure 36.

Parameter	Results
Total Grid Points	86
Total Defended Grid Points	86
Total Missed Grid Points	0
Total Grid Points with One Layer	86
Total Percent Footprint Defended (P_{fd})	100.0%
Probability of Intercept (P_i)	0.714

Table 31. Alternative C DAF Performance Summary

Figure 36. Alternative C DAF coverage

E. SUMMARY OF ALTERNATIVES REFINEMENT

A DAF performance summary of the Baseline system and each EBMD Alternative system is provided in Table 32. The placement, number and capability of each system had a significant impact on the percentage of footprint defended and the probability of intercept. When multiple systems were able to defend the same grid point, the probability of intercept for the area defended increased significantly as shown with Alternative B. One highly capable and strategically placed system, such as the Aegis Ashore system represented in Alternative C, could defend the entire area; however, with only one defense layer the probability of intercept was lower than some other EBMD Alternatives. This probability would increase by firing multiple interceptors.

Parameter	EBMD Alternative					
	BL	A	B.1	B.2	B.3	C
Total Grid Points	87	88	88	88	88	86
Total Defended Grid Points	61	67	79	85	88	86
Total Missed Grid Points	26	21	9	3	0	0
Total Grid Points with Four Layers	0	0	0	0	14	0
Total Grid Points with Three Layers	0	0	0	8	32	0
Total Grid Points with Two Layers	0	57	60	67	22	0
Total Grid Points with One Layer	61	10	19	10	20	86
Total Percent Footprint Defended (P_{fd})	70.1%	76.1%	89.8%	96.6%	100.0%	100.0%
Probability of Intercept (P_i)	0.614	0.676	0.780	0.869	0.905	0.714

Table 32.   DAF Performance Summary

VIII. LIFE CYCLE COST (LCC) ANALYSIS

A.   LIFE CYCLE COST ANALYSIS PROCESS

The life cycle cost (LCC) provided insight to the fiscal requirements for fielding the EBMD Alternatives. The LCC analysis process (Figure 37) evaluated various component systems identified during the alternatives generation process, to include Aegis ship, Aegis Ashore, THAAD, AN/TPY-2, and PAC-3. These life cycle costs include the associated costs to perform research and development (R&D), production and construction (P&C), operation and support (O&S), and disposal. Those costs were used to inform the decision making process during the analysis of alternatives.
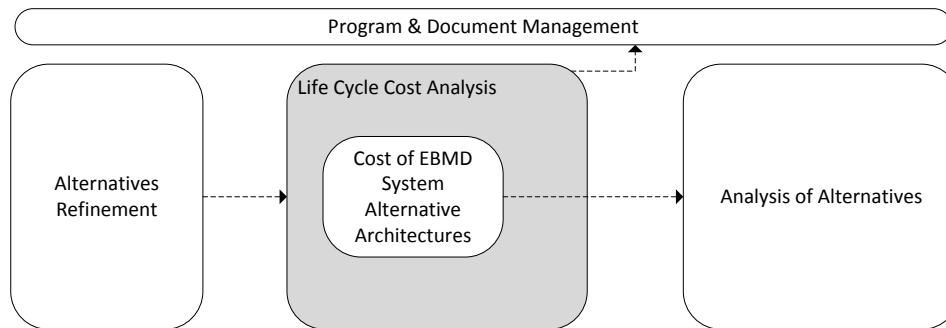
Figure 37.   LCC Analysis Process

To assist in the derivation of the individual cost activities related to a system life cycle, the cost breakdown structure (CBS) was used (Blanchard 2011, 577–612). The CBS incorporates a top level costing effort across respective activities to account for the procurement, operation, sustainment, and disposal of each EBMD Alternative. The high-level CBS elements were broken down by the following life-cycle phases.

B.   RESEARCH AND DEVELOPMENT COSTS

The R&D phase consists of costs realized early in the life cycle process. These costs focused primarily on the research of what capabilities exist and what capabilities will be present in the future to help build a successful EBMD system. Minimal R&D

investment for the EBMD components was required as these are technologies with proven records. The R&D costs attributed to the EBMD Alternatives are the following:

- System Management
- Systems Engineering
- Systems Planning, Research, and Development
- Systems Test and Evaluation
- System Documentation

C. PRODUCTION AND CONSTRUCTION COSTS

The production and construction costs are the expenses associated with the management, manufacturing, construction, quality control, and initial logistics support used to develop a system. The production and construction costs were included in the LCC to evaluate the different EBMD Alternative architectures. This phase takes into consideration the recurring costs, nonrecurring costs, and inventory costs of a given component. It also includes the costs required for the support equipment and procedural manuals in conjunction with new equipment training.

D. OPERATION AND SUPPORT COSTS

The operation and support costs are the highest expenses for the majority of the components. The O&S costs constitute the required expenses associated with the operation and maintenance of the components. Personnel, training, and facilities make up the costs for the operations of the components.

For the EBMD Alternatives, most of the components are mobile having a requirement for fuel and maintenance. The Aegis Ashore, being land-based, is the only component requiring an operations facility.

An O&S cost required for continuous operation of each component over time was calculated. This expense included storage, supply, maintenance, and training to carry the EBMD system through a 10-year life cycle.

Technological advancement over time will cause significant risk in our system if chosen technologies cannot meet performance objectives or become obsolete. The current strategy in Europe calls for a 10-year life cycle to provide adequate defenses. With a 10-

year life cycle, the cohort felt it could mitigate a performance shortfall or the onset of obsolescence. The technology in the EMBD components must meet the fast-paced development of threat capabilities during this 10-year period. The 10-year life cycle costs for the EBMD Alternatives include technical/maintenance support that may be required such as upgrades, refurbishments, and/or system troubleshooting.

E.   DISPOSAL COST

Disposal costs will be incurred when the EBMD system reaches the end of its operational life. The equipment and components that reach a non-repairable state will be disposed of in accordance with DoD regulations and with environmental considerations. The remaining components that are operational and repairable will be stripped down and repurposed to another project with a similar objective.

F.   COST ANALYSIS

The figures used to get the cost estimates for the components came from the MDA Budget for Fiscal Year 2013 (FY13) procurement budget (Office of the Under Secretary of Defense 2012). To develop the costs for each EBMD Alternative the cohort extrapolated the budgeted expenses from the MDA FY13 budget al.though not explicitly found during research, the estimated O&S costs were derived using the Operations and Maintenance Costs from the MDA Budget for FY13. The disposal costs were not readily available either, but the cohort was able to establish them through estimations and assumptions made between professional experience and the labor needed for the dismantling and removal of parts. Table 33 shows the systems composition for all the EBMD Alternatives.

EBMD Alternative					
Baseline	**A**	**B.1**	**B.2**	**B.3**	**C**
1 Aegis ship	2 Aegis ships	2 Aegis ships	2 Aegis ships	2 Aegis ships	1 Aegis Ashore
1 AN/TPY-2 Radar	1 AN/TPY-2 Radar	1 AN/TPY-2 Radar	1 AN/TPY-2 Radar	1 AN/TPY-2 Radar	1 AN/TPY-2 Radar
6 PAC-3		1 THAAD	2 THAADs	3 THAADs	

Table 33.   EBMD Alternatives

Since the EBMD system comprises several large components, the first step in the cost analyses was to find the single item costs of each component. The costs associated with the individual components can be found in Appendix D: Life Cycle Cost Analysis Data. Figure 38 displays the 10-year program costs (in billions) for the various components that make up the EMBD Alternatives.

	Total R&D Costs	Total P&C Costs	Total O&S Costs	TOTALS
PAC-3	$0.07	$1.04	$2.53	$3.63
THAAD	$0.03	$2.15	$4.70	$6.88
AN/TPY-2	$0.71	$0.33	$0.09	$1.12
Aegis Ashore	$0.11	$1.32	$2.93	$4.37
Aegis	$0.11	$1.32	$3.01	$4.44

Cost ($B)
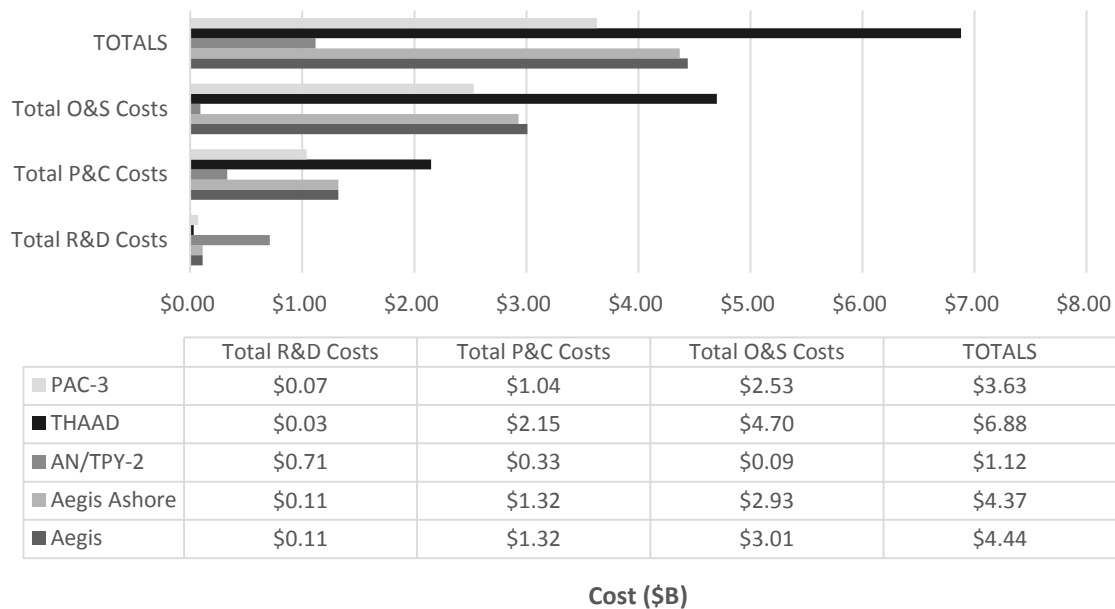
Figure 38.   EBMD Component 10 Year Costs in Billions (Disposal Costs Not Shown Due to Being Too Low to Show on Graph),

The THAAD accounted for the greatest expense of all the EBMD Alternative components. Its total cost was approximately $6.88 billion. The production and

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construction, and operation and support activities were the major cost contributors for the THAAD. Driving the expense of the THAAD was its missile requirement. The second most expensive component was actually the Aegis ship and its Aegis Ashore variant. Like the THAAD, the cost driver for the Aegis components was the SM-3 missile requirement. Much like the Aegis variants and THAAD, the PAC-3 also required a vast number of missiles to be effective. Unlike the rest of the components, R&D and production costs were the main drivers for the AN/TPY-2 Radar.

The Aegis Ashore is a new land-based capability that will incorporate the same BMD components as the ship variant (Missile Defense Agency 2013b). The Aegis Ashore had comparable costs to the Aegis ship with the exception of the full ship crew requirement and the fuel costs.

With the component costs established, the cohort was able to create a time-phased graphic, Figure 39, to display cost per EBMD Alternative per year for 10 years. The time-phased costs graph presents the costs from initiation of the EBMD system development through their operational length of time requirement.
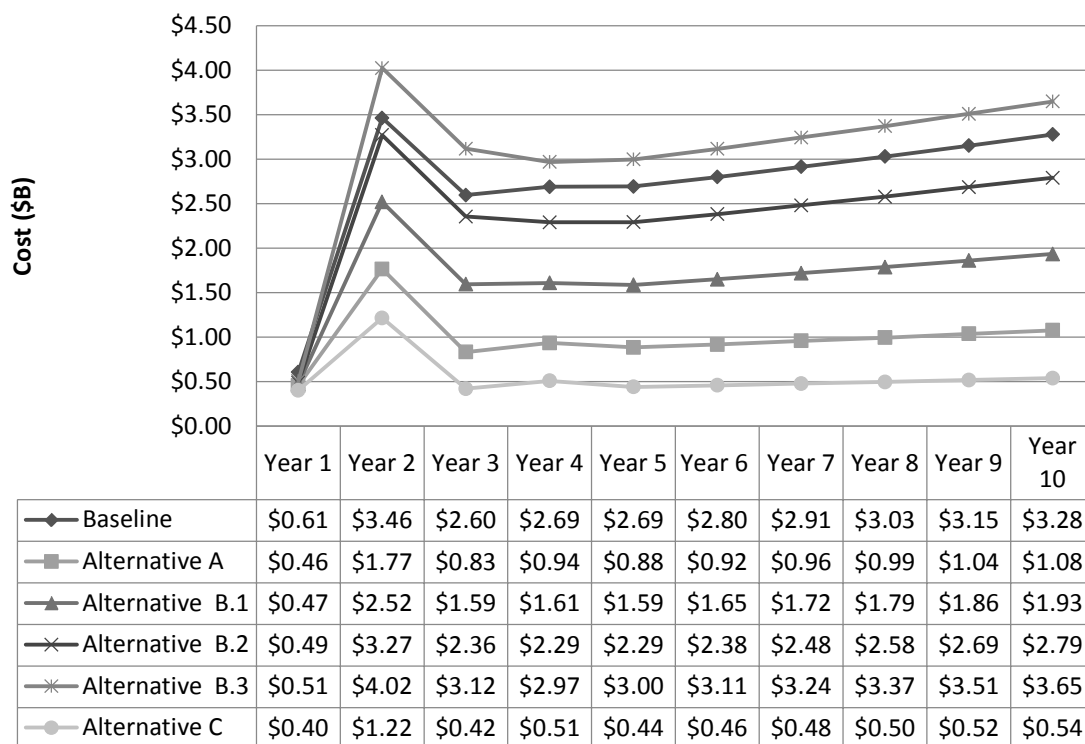
Figure 39.   EBMD Alternative Time-Phased Costs

Lastly, the cohort was able to derive the LCC values for the EBMD Alternatives from the estimated total costs generated from Figure 38. The estimated total costs for each EBMD Alternative were achieved by adding all the associated costs amongst the varying components with respect to each EBMD Alternative's configuration, which can be found in Table 33. Table 34 depicts these totals for each of the EBMD Alternatives.

Cost	EBMD Alternative					
	Baseline	**A**	**B.1**	**B.2**	**B.3**	**C**
Total R&D Costs	$1.24	$0.93	$0.97	$1.00	$1.03	$0.82
Total P&C Costs	$7.88	$2.97	$5.12	$7.27	$9.42	$1.65
Total O&S Costs	$18.25	$6.10	$10.80	$15.50	$20.19	$3.02
Total Disposal Costs	$0.0050	$0.0021	$0.0027	$0.0033	$0.0039	$0.0012
TOTALS	$27.37	$10.01	$16.89	$23.77	$30.65	$5.49

Table 34.   EBMD Alternative 10-Year Costs in Billions

G.   SUMMARY OF LCC ANALYSIS

Alternative B.3 was the most expensive option with a cost of approximately $30.65 billion. Alternative B.2 was the median option of all the EBMD Alternatives with a cost of $23.77 billion. Alternative C had the smallest cost ($5.49 billion) because of the single requirement of an Aegis Ashore and an AN/TPY-2 radar.

Alternative C had a similar configuration to Alternative A, the difference being the ship and ashore variants. Alternative A contained the ship variant, and was double the cost, while Alternative C included the future capability of the Aegis Ashore. They both had an AN/TPY-2 Radar. Aegis Ashore seemed to be a high cost effort at first, yet it is comprised of the same proven weapon system, sensors, and combat control technology as an Aegis ship, mitigating any increased cost risks. As for the production and construction costs for the Aegis Ashore, the cohort is less confident in the estimates because one has never been built.

Overall, operation and support exhibited a larger expenditure in comparison to the remaining cost activities, representing 55% to 66% of the total cost for each of the applicable EBMD Alternatives. These expenditures were more evident with components that contained a missile capability.

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IX. ANALYSIS OF ALTERNATIVES

A. ANALYSIS OF ALTERNATIVES PROCESS

This analysis of alternatives process (Figure 40) made use of a set of evaluation measures defined during the requirements analysis that were reflective of stakeholder objectives. Values for each EBMD Alternative's evaluation measures were populated from metrics generated during the alternative refinement process. These metrics were then used to compare each EBMD Alternative to one another relative to associated life cycle cost values. A decision evaluation display provided a visual tool to analyze disparities between EBMD Alternatives and select a path forward for system acquisition (Blanchard 2011).
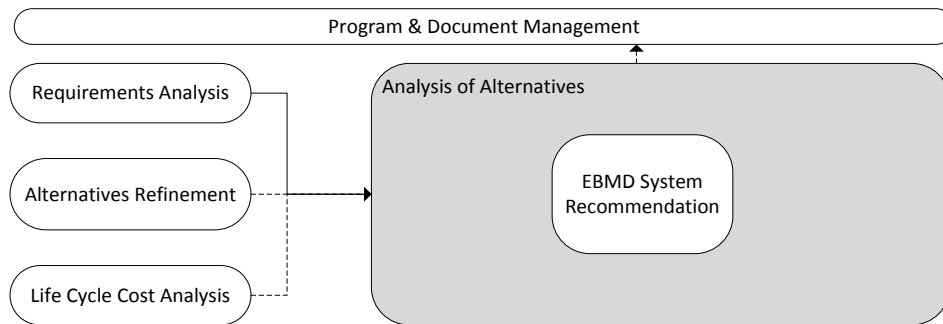
Figure 40.   Analysis of Alternatives Process

B. CRITERIA SELECTION

The criteria selected for evaluation of the EBMD Alternatives was based on a defined set of evaluation measures established during requirements analysis. The evaluation measures were outlined in the value system discussion of Chapter III. The measures included probability of intercept (P_i) and percent footprint defended (P_{fd}). The evaluation measures were established as a response to the high level stakeholder needs. These needs included the abilities to: defend against ballistic missile threats; adapt to changing technologies; and recognize current budget constraints. The consideration of probability of intercept as an analysis criteria established the effectiveness of a given

EBMD Alternative to successfully engage a threat, thereby providing a systematic defense against ballistic missile threats. Percent footprint defended accounted for the effect of changing technologies on range capability of ballistic missile threats. Finally, the consideration of system life cycle cost (LCC) for each EBMD Alternative was incorporated to help ensure the EBMD Alternatives provide an economically sustainable solution.

C.   EVALUATION MEASURES

Data sets from each EBMD Alternative were collected based on outputs from the Discrete Element Simulation and Scenario Based Simulation results. Table 35 shows a summary of evaluation measure values determined from Chapter VII. Each evaluation measure is plotted with its corresponding Baseline value in Figure 41 and Figure 42.

Evaluation Measure		EBMD Alternative					
		Baseline	A	B.1	B.2	B.3	C
Probability of Intercept	P_i	0.614	0.676	0.780	0.869	0.905	0.714
Percent Footprint Defended	P_{fd}	70.1%	76.1%	89.8%	96.6%	100%	100%

Table 35.   Comparison of Evaluation Measures
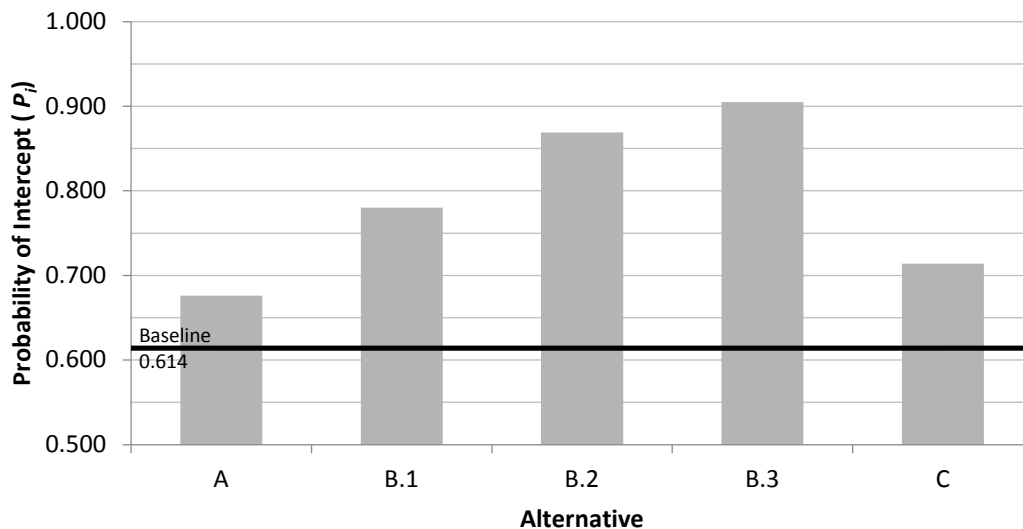
Figure 41.   Comparison of Probability of Intercept

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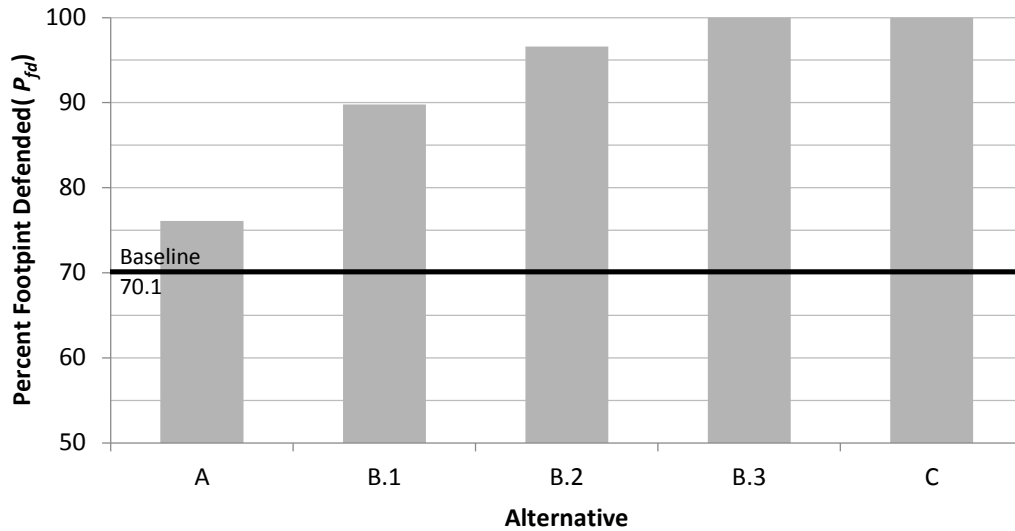
Figure 42.   Comparison of Percent Footprint Defended

D.   DECISION EVALUATION DISPLAY

The decision evaluation display provides a means to present disparities evident in the set of multiple alternatives (Blanchard 2011). The collected data for each EBMD Alternative relative to measures for system evaluation were plotted against an objective measure for analysis (Figure 43). In this case, the objective measure used was the life cycle cost of each EBMD Alternative.

Each EBMD Alternative is represented by a column in the display tool. The main x-axis of the decision evaluation display represents the life cycle cost as an objective measure. The life cycle cost is displayed as increasing cost from left to right. The y-axes toward the left of the plot represent the multiple evaluation measures for analysis. The x-axis of this plot does not intersect the y-axes at zero. Each y-axis is representative of zoomed scaling. Baseline values have been included for a complete comparison. These Baseline values are represented as horizontal dotted lines connecting to specific evaluation measures. Finally, the specific values for each of the alternative measures, as determined through M&S, are plotted as triangles and circles placed accordingly along each EBMD Alternative.
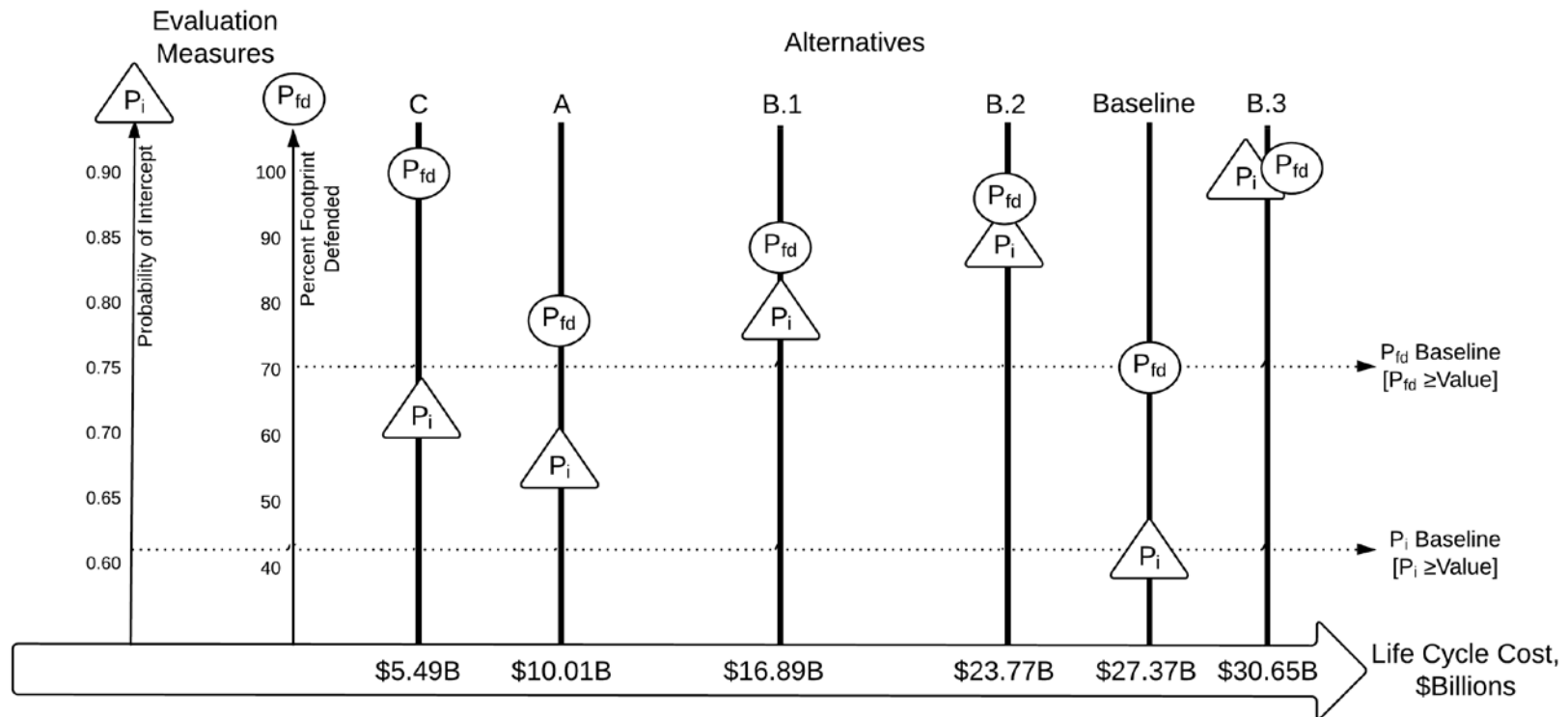
Figure 43.   Decision Evaluation Display

E.   VALUE ANALYSIS

EBMD Alternatives were compared relative to their associated values for all evaluation measures (Research Question 5). Alternative A exhibited the lowest values for each evaluation measure. Alternative C exhibited varying performance levels dependent on the evaluation measure chosen. Alternative C maintained the second lowest probability of intercept, yet the highest percentage of footprint defended. The three variations of Alternative B (B.1 through B.3) performed with increasing capability as components were added for each variation.

1.   Probability of Intercept

All EBMD Alternatives performed better than the Baseline system, with Alternatives C and A exhibiting the lowest probabilities of intercept relative to the Baseline system. All variants of Alternative B performed better than the Baseline system with increasing performance evident as components were added for each variation.

2.   Percentage of Footprint Defended

All EBMD Alternatives performed better than the Baseline system value with Alternatives B.3 and C achieving full coverage of the footprint defended.

3.   Decision Evaluation Display Analysis

This analysis allowed for the consideration of evaluation measures relative to the associated life cycle cost for each EBMD Alternative. In addition to the inclusion of evaluation measure values of the Baseline system, a separate axis was added to the display tool to represent the cost of the Baseline system. In comparison to Alternatives A through C, the Baseline system exhibited the second highest life cycle cost. Alternative B.3 maintained the highest life cycle cost of all EBMD Alternatives, including the Baseline system. Alternative C exhibited the lowest life cycle cost with associated values for both evaluation measures exceeding the Baseline system. Alternative A was also identified at the lower end of the life cycle cost spectrum; however the probability of intercept and percent footprint defended displayed by this EBMD Alternative were below

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the levels exhibited in Alternative C. Both performance and cost of Alternatives B.1 through B.3 increased in each iterative variation with the introduction of multiple THAAD interceptor batteries. Alternatives B.1 through B.3 were characterized by probability of intercept and percentage of footprint defended values exceeding those attained by the Baseline system. The life cycle costs of Alternatives B.1 and B.2 were lower than the Baseline system, while Alternative B.3 exhibited a cost 12% higher than the Baseline system.

X. CONCLUSIONS

A. EBMD ARCHITECTURE RECOMMENDATION

To protect European Nations and their allies, it is critical to design a BMD system that adapts to evolving threats, changing technology, and budget constraints. A European BMD system solution cannot depend on an approach that locks into technology for a fixed term but is interoperable with the changing environment. Adopting this strategy will result in improved ballistic missiles reaching assets that should be protected by aging systems. Although there is a diversity of improved ballistic missile defense systems today, the challenge is producing and fielding them within a limited timeframe. To satisfy the needs of the stakeholders, the EBMD system had to use existing systems with mature technology readiness to combat threats to Europe.

Displaying system performance and life cycle cost in a single analysis tool aided in visualizing differences between solutions as well as consideration of system trade-offs. Alternative B.3 exhibited the greatest system effectiveness independent of cost, while Alternative C presented the most cost-effective solution, independent of system performance. Although Alternative B.3 exhibited the highest probability of intercept with a fully defended footprint, this alternative also required the highest life cycle cost, exceeding the cost of the Baseline system. Alternatives A and C provided system effectiveness exceeding the baseline system as well, but at life cycle costs 20.2% to 36.2% of the Baseline system. However, Alternative C exhibited greater effectiveness of both probability of intercept and percent footprint defended at a lower cost than Alternative A. Alternatives B.1 and B.2 provided increased performance in probability of intercept in comparison to Alternatives A and C, but at an increased life cycle cost. As the lowest cost solution while maintaining system effectiveness values exceeding those of the Baseline system, Alternative C should be considered for system acquisition.

B.   RESEARCH RESULTS

In Chapter I of this report, five questions were generated to evaluate the EBMD problem. The following summarizes answers that were substantiated in the body of the report.

1.   What Are The Primary Regional Threats?

The primary regional threats are Iran and North Korea, which are capable of inflicting serious damage to the U.S. or its allies. (Missile Defense Agency 2012c).

2.   What Are The Needs Of The Stakeholders?

The primary needs of the stakeholders are the ability to engage and neutralize threats, and maximize footprint defended while keeping life-cycle cost to a minimum. The needs were incorporated into evaluation measures as follows:

- Probability of intercept, P_i, is the probability of the EBMD system to successfully engage a threat.
- Life Cycle Cost, LCC, is the sum of all recurring and non-recurring costs over the full life cycle of the system.
- Percent Footprint Defended, P_{fd}, is the ratio of footprint defended area to the area intended to be defended.

3.   What Are The Available Solutions?

Available existing solutions to protect European nations are: Aegis ships, THAAD, PAC-3, and AN/TPY2. These are existing systems that fulfill some required functionality for BMD. However, none of these are complete solutions to the problem, and none can successfully address all of European BMD as standalone systems.

4.   What Are The Existing System Limitations?

Careful evaluation of the issues in the EBMD domain eventually started to suggest three common themes that could be addressed from a systems engineering perspective: evolving threats, changing technology, and budget constraints. These problems were consistently cited among multiple stakeholders, spanned many BMD

systems, and required solutions that could be reached using the tools and techniques available to a systems engineer.

Current systems cannot adapt to changing technology because each component acts as a standalone solution. The budget suffers from increased cost because the components are standalone systems with independent acquisition strategies and varied mission requirements. In addition, lacking a systems of systems approach, the existing standalone systems cannot effectively adapt as threats are evolving.

5.   What Viable Solutions Can Be Formulated?

Viable solutions were formulated using existing weapon systems: Aegis ships, THAAD, PAC-3, and AN/TPY2. The systems were used to generate a Baseline and develop different EBMD Alternatives that performed at least as well as the Baseline. Initial experimentation with the PAC-3 interceptor showed its limited range severely restricted its effectiveness in the model to intercept the threat missiles. As a result, the cohort included the PAC-3 in modeling the Baseline system, but did not use the PAC-3 when modeling EBMD Alternatives. Alternative C was the preferred viable solution which consisted of one Aegis Ashore and one AN/TPY-2 Radar.

C.   FUTURE WORK

1.   Stakeholder Analysis

Through this research, the cohort learned that MDA is exempt from traditional joint requirements determination although they are required to work closely with combatant commands when developing capabilities (GAO 2011, 4). The GAO stated the lack of clear guidance from presidential policy to senior DoD officials led BMD stakeholders to make different assumptions about desired end states (GAO 2011, 12). The cohort made numerous attempts to locate stakeholders with no avail; the analysis was based solely on document research. Any future work should include coordination with appropriate combatant commands to ensure stakeholder requirements meet the needs of the end-user.

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2. Threat Analysis

While the cohort was able to locate research pertaining to the capabilities of Iran's missile types, it was not able to find a definitive source for the number of missiles Iran possesses. Actual numbers of the missiles are not publicly provided by the U.S. government (GAO 2011, 21). Scenarios were developed to understand the efficacy of EBMD system components and provide a set of EBMD Alternatives for analysis while remaining in the public domain. Future work should be performed matching EBMD Alternatives against best estimates of Iranian missile quantities with the understanding the work would not remain in the public domain.

3. Functional Analysis

The cohort learned that existing systems can complete all high level functions required to defend Turkey from ballistic missiles originating from Iran. Through M&S, the cohort determined several architectures have acceptable performance with the assumptions made during this project. However, as presented in Chapter VI, a typical battle delay for an interceptor would range between 8–20 seconds. The performance level begins to drop after 8 seconds and was not even simulated at 20 seconds because of degraded performance. Future work should focus on a deeper understanding of the battle delay. The BCN was considered outside the system during this project. In addition, BCN and communication with decision makers should be explored in future work. Due to the lack of resources and system parameters, the timing aspects could not be modeled in COREsim. Once a functional analysis is completed, the M&S should be focused on the timing aspects to ensure the required functions can be completed in sufficient time to allow successful engagements.

4. Modeling and Simulation

The M&S phase showed how the functions behaved and provided the data to provide a sound recommendation. Limitations were encountered with the particular modeling software used to simulate the scenarios. Academic licenses limited the use of

STK. If funds were available, the cohort could have accessed functions such as the STK Analyzer to provide additional probability metrics.

5.   **LCC**

The LCC presented an opportunity to look at the cost of the various EBMD Alternatives. Future cost analysis should also look at currently immature technology that could be mature at the end of 10-years. For example the Aegis ships, Aegis Ashore, and THAAD are completely dependent on kinetic effectors (missiles) to be effective, however, non-kinetic technology such as lasers or electronic warfare, might yield cost-effective EBMD Alternatives in the future.

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APPENDIX A. PROBLEM SPACE EXPLORATION DATA

The following tables represent data used during the mission needs analysis portion of problem space exploration.

Table 36 lists known Iranian threat missiles with their basic attributes. Those in an operational or near-operational state that pose a threat to Turkey were chosen for M&S. Korean missiles are included as well for context and because Iranian missiles are largely based on Korean technology.

COUNTRY	NAME	CLASS	RANGE MAX (km)	PAYLOAD MAX (KG)	STAGES	PROPELLANT	STATUS
Iran	Fateh A-110	SRBM	210	500	1	Solid	Operational
	Shahab 1	SRBM	330	1000	1	Liquid	Operational
	Shahab 2	SRBM	700	989	1	Liquid	Operational
	Shahab 3	MRBM	1,280	1158	1	Liquid	Operational
	Shahab 3 Variants	MRBM	2,500	800	1	Liquid/Solid	Development
	Sejil 2	MRBM	2000	1500	2	Solid	Presumed Operational
	Sejjil Variants	MRBM	2,500	1000	2	Solid	Development
	Ghadr 110	MRBM	1,800	1000	2	Liquid/ Solid	Development
	Ghadr 110A	MRBM	2,500	1000	3	Liquid/ Solid	Development
	Shahab 4	MRBM	2,896	1000	3	Liquid/Solid	Development
	Shahab 5	MRBM / ICBM	4,300	1000	3	Liquid/Solid	Development
	Shahab 6	ICBM / SLV	6,200	1000	3	Liquid/Solid	Development
N Korea	Taepo Dong 1	MRBM	2,000	750	2	Liquid	Development
	Taepo Dong 1 SLV	IRBM	5,000	750	3	Liquid/Solid	Development
	Taepo Dong 2	ICBM	15,000	1000	3	Liquid	Development

Table 36.   Iranian Ballistic Missile Threat Matrix (From George C. Marshall and Claremont Institutes 2013a)

Table 37 lists characteristics of various threat missiles found through research. These values were used to find the most-similar missile provided in MFT.

NAME	PAYLOAD (kg)	BURN TIME (sec)	THRUST (kgf)	Speed (km/s)	HEIGHT (m)	WIDTH (m)
Fateh A-110	500				8.9	0.61
Shahab 1	985 - 1,000	62 - 64	13,000		10.9	0.88
Shahab 2	750 - 989	--			10.9	0.88
Shahab 3	760 - 1,158	110	26,000	2.0–2.4	15.5	1.25a
Shahab 3 Variants	800			2.0–2.4	17.0	1.25a
Sejjil Variants	650 - 1,000				17.6	1.25
Ghadr 110	650 - 1,000	107–121			15.9	
Ghadr 110A	650 - 1,000					
Shahab 4	250 - 1,000	293	26,000			
Shahab 5	700 - 1,000	120/110/100	104,000/13,000/UNK			
Shahab 6	500 - 1,000					

Table 37.　　　　Physical Characteristics of Iranian Ballistic Missile Threats

Table 38 lists the five most-populous cities in Turkey. This table was used to determine potential high-value targets for Iran. The two largest cities were used in the M&S effort as the likeliest targets.

City	Distance from Tabriz (km)	Coordinates	Range Threat
Istanbul	1518	41.040871°N, 28.986179°E	MRBM
Ankara	1180	39.866667°N, 32.866667°E	MRBM
Izmir	1676	38.4333° N, 27.1500° E	MRBM
Bursa	1507	40.1833° N, 29.0500° E	MRBM
Adana	976	37.0000° N, 35.3167° E	SRBM

Table 38.　　　　Five most-populous cities in Turkey with coordinates and distances from Tabriz (From Butler 2009)

Table 39 lists those locations in Turkey and Europe of military importance. These were listed to determine possible targets for Iranian missiles. Kürecik, the location of the AN/TPY-2 radar, was chosen as a prime target for Iran as it provides missile detection capability for most of western Iran.

Item	Country	City	Distance from Tabriz (km)	Coordinates
U.S. Air Base	Turkey	Incirlik	470	37.0019° N, 35.4258° E
U.S. X-band radar	Turkey	Kürecik	750	38.0667° N, 38.0167° E
PAC-3, Dutch	Turkey	Gaziantep	794	37.0667° N, 37.3833° E
PAC-3, German	Turkey	Kahramanmaras	850	37.5833° N, 36.9333° E
PAC-3, U.S.	Turkey	Adana	976	37.0000° N, 35.3167° E
U.S. Naval Support Activity	Greece	Crete (Souda Bay)	1,999	35.2100° N, 24.9100° E
EUCOM HQ	Germany	Stuttgart-Vaihingen	3,188	48.7767° N, 9.1775° E
Ramstein Air Base	Germany	Remscheid	3,370	49.4375° N, 7.6014° E

Table 39.　　　　Selected Military Locations within European NATO Countries and Allies (From Coffey 2012; Geobytes 2013)

Cities or other locations in Iran that are known to support missile development or launch capabilities are listed in Table 40. These were listed to identify where threat missiles were coming from, and is useful for discerning ranges and targets. It was also critical for the IFT DAF scenarios to know from where a missile was launched so as to determine its targetable range.

Launch Location	City	Coordinates	Missile Type	Usage
Tabriz Missile Base	Tabriz	38.0833° N, 46.2833° E	Shahab-3	Silo Launcher
Imam Ali Missile Base	Khorramabad	33.4667° N, 48.3500° E	Shahab-3	Silo Launcher
Qom Space Center	Qom	34.65000°N 50.90000°E	Shahab-3	Space Testing
Emamshahr Space Center	Shahrud	36.42000°N 55.02000°E	Shahab-3	Space Testing
Semnan Missile Complex	Semnan	36.00000°N 54.00000°E	All	Test Range and Production

Table 40.   Iranian Ballistic Missile Launch Locations (From The Nuclear Threat Initiative, 2013; The Nuclear Threat Initiative 2011a; The Nuclear Threat Initiative 2011b)

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APPENDIX B. MODELING AND SIMULATION ANALYSIS DATA

The following tables were used during M&S to construct simulations and scenarios. Table 41 and Table 42 show the parameters of various IFT simulations performed for 1VM and DAF scenarios, respectively. In each table, each row represents a different scenario.

For the 1VM scenarios in Table 41, the first column represents how many threat missiles were modeled. The second through fourth columns represent how many of each type of interceptor battery were included. The fifth column represents the range of battle delays modeled, where a new simulation was performed for each of the values in the range. The sixth column represents the percentage of the threat missiles hit at different battle delay values. The seventh and eighth columns contain text entered by the modeler to distinguish scenario files and notes on those scenarios.

# Missiles	# Aegis	# PAC-3	# THAAD	Battle Delay (s)	Success?	Case	Notes
1	2	0	0	8 - 14	100% @ 8s, 0% @ 9s"	S1	For all Baselines, only 1 Aegis is engaging 35.6x32.5 to 36.0x33.8 Lat/Long
2	2	0	0	8–9	100% @ 8s, 0% @ 9s	S3	
2	2	0	0	8–9	100% @ 8s, 0% @ 9s	S4	
10	2	0	0	8–16	100% @ 4s, 80 % @ 6s, 60% @ 8s, 40 % @ 10–16s	S5	Incirlik missiles intercepted better
3	1	0	0	8–16	100% @ 8s, 66% @ 9–16s,	Aegis-Med	Questionable on why third cannot be hit. Aegis in NE Med
3	1	0	0	16–20	100% @ 20s	Aegis-BlkSea	Aegis in SE Black Sea.
3	0	0	1	8–16	33 %	THAAD1	Kürecik. Sejils fly too high for THAAD
3	0	0	3	0–12	0%	THAAD-EastTurkey-3batt	Spread across Turkey's East border, but got no hits. Not even when moving to SRM-350 interceptor
3	0	0	1	0–16	0–33%	THAAD-East Turkey	Tried many locations around E. Turkey. Best I could do was to shoot down the Shahab. Altitude on Sejils too high. I also tried with the SRM-350 and was able to shoot down one of the Sejils also, bringing me to 66%

Table 41. Results of Varied IFT 1VM Scenarios

With the DAF scenarios, IFT tries to defend each grid point in a defined footprint, and the results are shown in Table 42. The first through third columns represent how many of each type of interceptor battery were included. The fourth column represents the range of battle delays modeled (with each a new simulation performed for each of the values in the range). The fifth column represents the percentage of grid points defended. The sixth and seventh columns contain text entered by the modeler to distinguish scenario files and notes on those scenarios.

# Aegis	# PAC-3	# THAAD	Battle Delay	Success?		Notes
1	0	0	8–14	63.5%	DAF-Aegis-Med-Sejil	Get the 7 western grid points. Using MRI-1100 int.
1	0	0	14	69.8%	DAF-Aegis-BlkSea-Sejil	Used 1 degree granularity and Sejil2 missile
2	0	0	8–14	84.1%	Combined Aegis-Sejil	Calculated by summing the grid points covered by each Aegis DAF scenario.
1	0	0	14	65.8%	DAF-Aegis-Med-Shahab	Used the SRM3 missile
1	0	0	14	69.7%	DAF-Aegis-BlkSea-Shahab	Used the SRM3 missile
1	0	0	14	72.4%	Combined Aegis-Shahab	Used the SRM3 missile
0	0	1	8	23.4%	DAF-THAAD-Shahab	THAAD interceptor at 39.347 x 41.4
2	0	1	8–14	88.2%	Combined Aegis-Shahab + THAAD	
2	0	1	14	89.8%	All Combined	See Sheet 3 for filtering of grid points
2	0	2	8,14	89.8%	DAF-2THAAD-Shahab_[AB]	THAAD interceptor A at 40.211x40.0 and B at 38.222x40.0
2	0	2	8,14	96.6%	DAF-2THAAD-Shahab_[CD]	THAAD interceptor C at 40.211x41.4 and D at 38.222x41.4
2	0	2	8,14	95.5%	DAF-2THAAD-Shahab_[EF]	THAAD interceptor E at 40.0x41.4 and F at 37.7x41.4
2	0	2	8,14	95.5%	DAF-2THAAD-Shahab_[GH]	THAAD interceptor G at 40.0x42.3 and H at 37.7x42.3
2	0	2	8,14	96.6%	DAF-2THAAD-Shahab_[IJ]	THAAD interceptor I at 39.25x42.4 and J at 38.0x39.2
2	0	3	8,14	100.0%	DAF-3THAAD-Shahab	THAAD interceptor C at 40.211x41.4 and D at 38.222x41.4 and E at 37.0x37.9
1	0	0	10	100.0%	DAF-Aegis-Ashore	Aegis Ashore at 38.35x41.3, tested 100% coverage on both Shahab and Sejil grids.

Table 42.   Results of Varied IFT DAF Scenarios

Table 43 is sample IFT data, tabulated and merged from multiple DAF scenarios. The first two columns represent targetable grid points by the Sejil and Shahab missiles. These are combined, with duplicates removed, in column 3. Column 4 shows the subset of points that are defensible and column 5 shows those that are not. Column 5 shows the percentage of grid points not covered.

Sejil	Shahab	Unique Combined	Defended	Undefended	% Defended
36.1670 32.9032	36.1670 32.9032	36.1670 32.9032	36.1670 32.9032	36.8640 36.7742	0.897727273
36.8640 29.0323	36.8640 30.3226	36.8640 29.0323	36.8640 29.0323	36.8640 38.0645	
36.8640 30.3226	36.8640 31.6129	36.8640 30.3226	36.8640 30.3226	36.8640 39.3548	
36.8640 31.6129	36.8640 32.9032	36.8640 31.6129	36.8640 31.6129	37.5611 41.9355	
36.8640 32.9032	36.8640 34.1935	36.8640 32.9032	36.8640 32.9032	37.5611 43.2258	
36.8640 34.1935	36.8640 35.4839	36.8640 34.1935	36.8640 34.1935	38.2581 43.2258	
36.8640 35.4839	36.8640 36.7742	36.8640 35.4839	36.8640 35.4839	38.9552 40.6452	
36.8640 36.7742	36.8640 38.0645	36.8640 36.7742	37.5611 27.7419	40.3493 43.2258	
36.8640 38.0645	36.8640 39.3548	36.8640 38.0645	37.5611 29.0323	41.0464 43.2258	
37.5611 27.7419	37.5611 30.3226	36.8640 39.3548	37.5611 30.3226		
37.5611 29.0323	37.5611 31.6129	37.5611 27.7419	37.5611 31.6129		
37.5611 30.3226	37.5611 32.9032	37.5611 29.0323	37.5611 32.9032		
37.5611 31.6129	37.5611 34.1935	37.5611 30.3226	37.5611 34.1935		
37.5611 32.9032	37.5611 35.4839	37.5611 31.6129	37.5611 35.4839		
37.5611 34.1935	37.5611 36.7742	37.5611 32.9032	37.5611 36.7742		
37.5611 35.4839	37.5611 38.0645	37.5611 34.1935	37.5611 38.0645		
37.5611 36.7742	37.5611 39.3548	37.5611 35.4839	37.5611 39.3548		
37.5611 38.0645	37.5611 40.6452	37.5611 36.7742	37.5611 40.6452		
38.2581 26.4516	37.5611 41.9355	37.5611 38.0645	38.2581 26.4516		
38.2581 27.7419	37.5611 43.2258	37.5611 39.3548	38.2581 27.7419		
38.2581 29.0323	38.2581 30.3226	37.5611 40.6452	38.2581 29.0323		
38.2581 30.3226	38.2581 31.6129	37.5611 41.9355	38.2581 30.3226		
38.2581 31.6129	38.2581 32.9032	37.5611 43.2258	38.2581 31.6129		
38.2581 32.9032	38.2581 34.1935	38.2581 26.4516	38.2581 32.9032		
38.2581 34.1935	38.2581 35.4839	38.2581 27.7419	38.2581 34.1935		
38.2581 35.4839	38.2581 36.7742	38.2581 29.0323	38.2581 35.4839		
38.2581 36.7742	38.2581 38.0645	38.2581 30.3226	38.2581 36.7742		
38.2581 38.0645	38.2581 39.3548	38.2581 31.6129	38.2581 38.0645		
38.9552 27.7419	38.2581 40.6452	38.2581 32.9032	38.2581 39.3548		
38.9552 29.0323	38.2581 41.9355	38.2581 34.1935	38.2581 40.6452		
38.9552 30.3226	38.2581 43.2258	38.2581 35.4839	38.2581 41.9355		
38.9552 31.6129	38.9552 30.3226	38.2581 36.7742	38.9552 27.7419		
38.9552 32.9032	38.9552 31.6129	38.2581 38.0645	38.9552 29.0323		
38.9552 34.1935	38.9552 32.9032	38.2581 39.3548	38.9552 30.3226		
38.9552 35.4839	38.9552 34.1935	38.2581 40.6452	38.9552 31.6129		
38.9552 36.7742	38.9552 35.4839	38.2581 41.9355	38.9552 32.9032		
38.9552 38.0645	38.9552 36.7742	38.2581 43.2258	38.9552 34.1935		
39.6523 26.4516	38.9552 38.0645	38.9552 27.7419	38.9552 35.4839		
39.6523 27.7419	38.9552 39.3548	38.9552 29.0323	38.9552 36.7742		
39.6523 29.0323	38.9552 40.6452	38.9552 30.3226	38.9552 38.0645		
39.6523 30.3226	38.9552 41.9355	38.9552 31.6129	38.9552 39.3548		
39.6523 31.6129	38.9552 43.2258	38.9552 32.9032	38.9552 41.9355		
39.6523 32.9032	39.6523 30.3226	38.9552 34.1935	38.9552 43.2258		
39.6523 34.1935	39.6523 31.6129	38.9552 35.4839	39.6523 26.4516		
39.6523 35.4839	39.6523 32.9032	38.9552 36.7742	39.6523 27.7419		
39.6523 36.7742	39.6523 34.1935	38.9552 38.0645	39.6523 29.0323		
39.6523 38.0645	39.6523 35.4839	38.9552 39.3548	39.6523 30.3226		
40.3493 29.0323	39.6523 36.7742	38.9552 40.6452	39.6523 31.6129		
40.3493 30.3226	39.6523 38.0645	38.9552 41.9355	39.6523 32.9032		
40.3493 31.6129	39.6523 39.3548	38.9552 43.2258	39.6523 34.1935		
40.3493 32.9032	39.6523 40.6452	39.6523 26.4516	39.6523 35.4839		
40.3493 34.1935	39.6523 41.9355	39.6523 27.7419	39.6523 36.7742		
40.3493 35.4839	39.6523 43.2258	39.6523 29.0323	39.6523 38.0645		
40.3493 36.7742	40.3493 30.3226	39.6523 30.3226	39.6523 39.3548		
40.3493 38.0645	40.3493 31.6129	39.6523 31.6129	39.6523 40.6452		
41.0464 30.3226	40.3493 32.9032	39.6523 32.9032	39.6523 41.9355		
41.0464 31.6129	40.3493 34.1935	39.6523 34.1935	39.6523 43.2258		
41.0464 32.9032	40.3493 35.4839	39.6523 35.4839	40.3493 29.0323		
41.0464 34.1935	40.3493 36.7742	39.6523 36.7742	40.3493 30.3226		
41.0464 35.4839	40.3493 38.0645	39.6523 38.0645	40.3493 31.6129		
41.0464 36.7742	40.3493 39.3548	39.6523 39.3548	40.3493 32.9032		

Sejil	Shahab	Unique Combined	Defended	Undefended	% Defended
41.7434 32.9032	40.3493 40.6452	39.6523 40.6452	40.3493 34.1935		
41.7434 34.1935	40.3493 41.9355	39.6523 41.9355	40.3493 35.4839		
	40.3493 43.2258	39.6523 43.2258	40.3493 36.7742		
	41.0464 30.3226	40.3493 29.0323	40.3493 38.0645		
	41.0464 31.6129	40.3493 30.3226	40.3493 39.3548		
	41.0464 32.9032	40.3493 31.6129	40.3493 40.6452		
	41.0464 34.1935	40.3493 32.9032	40.3493 41.9355		
	41.0464 35.4839	40.3493 34.1935	41.0464 30.3226		
	41.0464 36.7742	40.3493 35.4839	41.0464 31.6129		
	41.0464 39.3548	40.3493 36.7742	41.0464 32.9032		
	41.0464 40.6452	40.3493 38.0645	41.0464 34.1935		
	41.0464 41.9355	40.3493 39.3548	41.0464 35.4839		
	41.0464 43.2258	40.3493 40.6452	41.0464 36.7742		
	41.7434 32.9032	40.3493 41.9355	41.0464 39.3548		
	41.7434 34.1935	40.3493 43.2258	41.0464 40.6452		
		41.0464 30.3226	41.0464 41.9355		
		41.0464 31.6129	41.7434 32.9032		
		41.0464 32.9032	41.7434 34.1935		
		41.0464 34.1935			
		41.0464 35.4839			
		41.0464 36.7742			
		41.0464 39.3548			
		41.0464 40.6452			
		41.0464 41.9355			
		41.0464 43.2258			
		41.7434 32.9032			
		41.7434 34.1935			

Table 43.   Sample IFT Data

APPENDIX C. MODELING AND SIMULATION SCRIPT DETAILS

This appendix holds the contents of two BASH scripts used to analyze the IFT XML output from DAF scenarios.

The first file, called compare.sh, takes as arguments two IFT DAF scenario output files and determines if any of the missed grid points from the first file are covered in the second file. If so, it re-computes the hit percentage, providing the ability to check the effectiveness of multiple interceptor batteries.

```
#!/bin/bash
# This script takes as arguments two IFT XML files (those with a .ift
extension).
# The script checks to see if the second file covers any grid points missed
by the
# first file and if so, it recomputes the hit percentage.
# Cameron Harr, April 2013

if [ $# -ne 2 ]; then echo "Usage: $0 <infile> <compare file>"; exit -1;fi

infile=$1
comparefile=$2
numgrids=$(egrep.exe "^ [0–9]+\..*" $infile| wc -l)
falsecount=0
plus=0
declare -a missarray=0
index=0

for i in `egrep.exe "^ [0–9]+\..*" $infile|grep false|awk '{print $3}'| \
        cut -d'G' -f2`; do
    gridpoint=$i
    if [[ "$gridpoint" != "" ]]; then
        falsecount=$((falsecount+1))
        #echo "gridpoint: $gridpoint"
        grep $gridpoint $comparefile | grep true | grep -v false
>/dev/null
        if [ $? -eq 0 ]; then
            plus=$((plus + 1))
        else
            templl=""
            templl=$(grep $gridpoint $infile|grep false|awk '{print $1"
"$2}')
            #echo $templl
            missarray[$index]="$templl"
            index=$((index+1))
        fi
    fi
done
count=$((numgrids-falsecount))
hit=$(awk 'BEGIN { print '$count'*100/'$numgrids' }')
```

```bash
echo "Orginal hit %: $hit%"
echo "Added $plus grids"
count=$((count+plus))
hit=$(awk 'BEGIN { print '$count'*100/'$numgrids' }')
echo "Combined hit %: $hit%"
echo "Missed grid points:"
for i in `seq 0 $index`; do
echo ${missarray[$i]}
done
```

The second file, called filtermisses.sh, takes as an argument a regular expression that includes all IFT DAF scenario files the user wishes to analyze. The script then determines all the unique grid points in the area and determines the percentage of those grid points covered and their layers of coverage. This was used to test multiple interceptor systems with multiple threat missiles all at the same time.

```bash
#!/bin/bash
# This script takes as an argument a regular expression (in quotes) to include
# multiple IFT DAF output XML files (those with a .ift extension). The script
# analyzes all the files included and determines all unique grid points. It
# then determines which of those grid points are defended by interceptors and
# computes the percentage of the area covered. It also outputs how many layers
# of coverage each grid point has to a .csv file.
# One can use this to analyze IFT scenarios with multiple missile types and
# multiple interceptors all at once to see how well an entire region is covered.
# Cameron Harr, April 2013


if [ $# -ne 1 ]; then echo "Usage: $0 <Filename search pattern> "; exit -1;fi

filter=$1
dupfile=duplicates.txt
aidx=0
dupcount=1
didx=0 #dup index
lidx=0 #line index
midx=0 #miss index
declare -a allpoints
declare -a dups
declare -a missedpoints

# Set for loop delimiter at newline
IFS=$(echo -en "\n\b")

# First collect all the targetable grid points, sort and filter duplicates
```

```
    for point in $(egrep.exe -h "^ [0-9]+\..*" $filter | grep true | sort| \
                awk '{print $1" "$2}' | uniq); do
        allpoints[aidx]=$point
        aidx=$((aidx+1))
    done
    let numall=$((aidx+1))

    # Then collect all the misses, sort and filter duplicates
    for point in $(egrep.exe -h "^ [0-9]+\..*" $filter | grep false | sort| \
                awk '{print $1" "$2}' | uniq); do
        missedpoints[midx]=$point
        midx=$((midx+1))
    done
    let nummissed=$((midx))

    # Collect duplicate "hit" grid points
    for point in $(egrep.exe -h "^ [0-9]+\..*" $filter | grep true | sort| \
                awk '{print $1" "$2}' | uniq -D); do
        dups[dupidx]=$point
        dupidx=$((dupidx+1))
    done

    echo "Processing layers of coverage..."
    # Blank the duplicate file then write out duplicates
    >$dupfile
    for point in `seq 0 $((dupidx-1))`; do
        #echo ${dups[point]}
        if [[ ${dups[point]} == ${dups[point+1]} ]]; then
            dupcount=$((dupcount+1))
            #echo $dupcount
        else
            echo -n ${dups[point]} | sed -e 's/  /,/g' >> $dupfile
            echo ,"$dupcount" >> $dupfile
            dupcount=1
        fi
    done

    # For each miss, see if there was a hit for it elsewhere
    echo Missed Points:
    for i in `seq 0 $((nummissed-1))`; do
        #echo "if ! grep \"${missedpoints[$i]}\" *-S*.ift | grep -v false ;
then"
        if grep "${missedpoints[$i]}" $filter| grep -v false >/dev/null; then
            nummissed=$((nummissed-1));
        else
            echo ${missedpoints[$i]}
        fi
    done

    numhit=$((numall - nummissed))
    phit=$(awk 'BEGIN { print '$numhit'*100/'$numall' }')

    echo
    echo "$nummissed out of $numall gridpoints were missed"
```

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APPENDIX D. LIFE-CYCLE COST ANALYSIS DATA

The following tables were used to construct the cost models for the EBMD Alternatives. Source cost data for Table 44 through Table 71 came from the 2012 Budget Report of the Office of the Secretary of Defense (Office of the Under Secretary of Defense 2012).

Table 44 was used to derive the R&D costs for the Aegis Ashore component. The years were staggered to reflect the length of time for the respective phase of the component development to commence, complete, and enter the next development phase, keeping in mind that all components saw identical phases and a 10-year life span.

Program Activity	Year 1	Year 2	Estimate Totals	Notes
Government				
System Management	$136,771	$142,242	$279,013	1 GS14 (opm.gov)
Systems Engineering	$415,742	$432,372	$848,114	1 GS13, 2 GS12s
Product Research & Design	$150,000	$156,000	$306,000	2 GS12s
System T&E	$150,000	$156,000	$306,000	2 GS12s
Contractor				
System Management	$140,000	$145,600	$285,600	
Product Research, Planning, and Design	$53,230,000	$55,359,200	$108,589,200	1 Aegis Ashore (v3.6.1), 1 SM-3 BlkIIB, 1 SM-3 BlkIIA
System Documentation	$70,000	$72,800	$142,800	1 Employee @ $70k
System T&E	$140,000	$145,600	$285,600	2 Employees @ $70k (Contractor will determine personnel, estimate will be adjusted according to contractor's proposal)
Total R&D Costs	$54,432,513	$56,609,814	$111,042,327	

Table 44. Aegis Ashore R&D Costs

Table 45 lists the values used to derive the production and construction costs for the Aegis Ashore component. These activities were used to estimate the costs to build the Aegis Ashore and what type of work/personnel was included in the accounting.

Program Activity	Year			Estimate Totals	Notes
	2	3	4		
Government					
System Management	$137,771	$143,282	$149,013	$430,066	1 GS14
Contractor					
System Management	$130,000	$135,200	$140,608	$405,808	
Manufacturing					
Recurring	$389,623,000	$405,207,920	$421,416,237	$1,216,247,157	Assuming 29 Interceptors/yr, 3 SM-3 BlkIB
Nonrecurring	$31,010,000			$31,010,000	1 AegisBMD (v3.6.1)
Quality Control	$124,000	$128,960	$134,118	$387,078	1 QA
Initial Logistical Support					
Supply Support	$71,300,000			$71,300,000	Initial Spare = 1 Operational Aegis, 1 AegisBMD (v3.6.1), 3 SM-3 BlkIB
Transportation and Handling	$150,000		$0	$150,000	Shipping and Handling
Technical Data	$87,000	$90,480	$94,099	$271,579	
Personnel, Equipment, and Training	$1,020,000	$1,060,800	$103,232	$2,184,032	
Total P&C Costs	$493,581,771	$406,766,642	$422,037,308	$1,322,385,720	

Table 45.   Aegis Ashore Production and Construction Costs

Table 46 lists the values used to derive the O&S costs for the Aegis Ashore component. The following activities were used to estimate the costs to operate and provide operational support for the Aegis Ashore and what type of work/personnel was including in the accounting.

Program Activity	Year 3	4	5	6	7	8	9	10	Estimate Totals
Government									
System Management[1]	$137,771	$143,281	$149,013	$154,973	$161,172	$167,619	$174,324	$181,297	$1,269,453
Operating Personnel[2]	$905,652	$941,878	$979,553	$1,018,735	$1,059,485	$1,101,864	$1,145,939	$1,191,776	$8,344,882
Unscheduled Maintenance[3]	$25,000	$25,000	$26,000	$27,040	$28,122	$29,246	$30,416	$31,633	$222,457
Maintenance Facilities	$0	$0	$7,000	$7,001	$7,002	$7,003	$7,004	$7,284	$42,294
Supply Support[4]		$0	$438,272,886	$455,803,802	$474,035,954	$492,997,392	$512,717,288	$533,225,979	$2,907,053,300
Maintenance Personnel Training[5]	$480,000	$672,000	$698,880	$978,432	$1,369,805	$1,917,727	$2,684,817	$2,792,210	$11,593,871
Test and Support Equipment	$1,000,000		$1,040,000	$0	$1,081,600	$0	$1,124,864	$1,169,859	$5,416,323
Transportation and Handling									$0
Total O&S Costs	$2,548,423	$1,782,160	$441,173,333	$457,989,984	$477,743,140	$496,220,852	$517,884,652	$538,600,038	$2,933,942,581
Notes									
1	1 GS14								
2	Aegis Cost Estimate as it was used as the template (Sources: http://www.dfas.mil/militarymembers/payentilements/militarypaytables.html,http://navysite.de/cg/cg47class.htm, http://www.navycs.com/2013-military-pay-chart.html#enlisted-paycharts). Costs include 30 E-4s@$24972, and 3 O-2s@$52164 (1/10th the manpower of an Aegis ship).								
3	General PM performed								
4	Assuming 29 Interceptors/yr, SM-3 BlkIB								
5	10 Personnel @ $48k (Personnel work for 10 years)								

Table 46.   Aegis Ashore O&S Costs

Table 47 lists the values used to derive the disposal costs for the Aegis Ashore component. The following activities were used to estimate the costs to dismantle and dispose of the Aegis Ashore and what type of work/personnel was included in the accounting.

Program Activity	Year 11	Estimate Totals	Notes
Government			
Program Engineer	$89,846	$89,846	1 GS-12
Support Personnel	$120,000	$120,000	5 E-4 Personnel @ $24k
Support Equipment	$25,000	$25,000	
Facilities	$7,000	$7,000	
Contractor			
Support Personnel	$120,000	$120,000	5 E-4 Personnel @ $24k
Support Equipment		$0	
Technical Data	$70,000	$70,000	1 Employee @ $70k
Transportation and Handling		$0	
Total Disposal Costs	$431,846	$431,846	

Table 47.   Aegis Ashore Disposal Costs

Table 48 was used to derive the R&D costs for the Aegis ship component. The years were staggered to reflect the length of time for the respective phase of the

component development to commence, complete, and enter the next development phase, keeping in mind that all components saw identical phases and a 10-year life span.

Program Activity	Year 1	Year 2	Estimate Totals	Notes
Government				
System Management	$136,771	$142,241	$279,012	1 GS14
Systems Engineering	$415,742	$432,372	$848,114	1 GS13, 2 GS12s
Product Research & Design	$150,000	$156,000	$306,000	2 GS12s
System T&E	$150,000	$156,000	$306,000	2 GS12s
Contractor				
System Management	$140,000	$145,600	$285,600	
Product Research, Planning, and Design	$53,230,000	$55,359,200	$108,589,200	1 AegisBMD (v3.6.1), 1 SM-3 BlkIIB, 1 SM-3 BlkIIA
System Documentation	$70,000	$72,800	$142,800	1 Employee @ $70k
System T&E	$350,000	$364,000	$714,000	2 Employees @ $70k (Contractor will determine personnel, estimate will be adjusted according to contractor's proposal)
Total R&D Costs	$54,642,513	$56,828,213	$111,470,726	

Table 48.   Aegis R&D Costs

Table 49 lists the values used to derive the production and construction costs for the Aegis ship component. These activities were used to estimate the costs to build the Aegis ships and what type of work/personnel was included in the accounting.

Program Activity	Year			Estimate Totals	Notes
	2	**3**	**4**		
Government					
System Management	$137,771	$143,281	$149,013	$430,065	1 GS14
Contractor					
System Management	$130,000	$135,200	$140,608	$405,808	
Manufacturing					
Recurring	$389,623,000	$405,207,920	$421,416,236	$1,216,247,156	Assuming 29 Interceptors/yr, 3 SM-3 BlkIB
Nonrecurring	$31,010,000			$31,010,000	1 AegisBMD (v3.6.1)
Quality Control	$124,000	$128,960	$134,118	$387,078	1 QA
Initial Logistical Support					
Supply Support	$71,300,000			$71,300,000	Initial Spare = 1 Operational Aegis, 1 AegisBMD (v3.6.1), 3 SM-3 BlkIB
Transportation and Handling	$150,000	$156,000	$162,240	$468,240	Shipping and Handling
Technical Data	$87,000	$90,480	$94,099	$271,579	
Personnel, Equipment, and Training	$1,040,000	$1,081,600	$124,864	$2,246,464	
Total P&C Costs	$493,601,771	$406,943,441	$422,221,179	$1,322,766,392	

Table 49.   Aegis Production and Construction Costs

Table 50 lists the values used to derive the O&S costs for the Aegis ships component. These activities were used to estimate the costs to operate and provide operational support for the Aegis ships.

Program Activity	Year								Estimate Totals
	3	4	5	6	7	8	9	10	
Government									
System Management [1]	$137,771	$143,281	$149,013	$154,973	$161,172	$167,619	$174,324	$181,297	$1,269,453
Operating Personnel[2]	$9,056,520	$9,418,781	$9,795,532	$10,187,353	$10,594,847	$11,018,641	$11,459,387	$11,917,762	$83,448,824
Unscheduled Maintenance[3]	$25,000	$25,000	$26,000	$27,040	$28,122	$29,246	$30,416	$31,633	$222,457
Maintenance Facilities	$0	$0	$7,000	$7,001	$7,002	$7,003	$7,004	$7,005	$56,015
Supply Support[4]		$0	$438,272,886	$455,803,802	$474,035,954	$492,997,392	$512,717,288	$533,225,979	$2,907,053,300
Maintenance Personnel Training[5]	$480,000	$672,000	$698,880	$978,432	$1,369,805	$1,917,727	$2,684,817	$2,792,210	$11,593,871
Test and Support Equipment	$1,000,000		$1,040,000	$0	$1,081,600	$0	$1,124,864	$1,169,859	$4,246,464
Transportation and Handling									$150,000
Total O&S Costs	$10,856,291	$10,266,063	$449,989,311	$467,158,602	$487,278,502	$506,137,629	$528,198,101	$548,155,887	$3,008,040,385
Notes									
1	1 GS14								
2	1 Aegis ship Crew (Sources: http://navysite.de/cg/cg47class.htm, http://www.navycs.com/2013-military-pay-chart.html#enlisted-paycharts) Costs include 300 E-4s@$24972, and 30 O-2s@$52164.								
3	General PM performed								
4	Assuming 29 Interceptors/yr, SM-3 BlkIB								
5	10 Personnel @ $48k (Personnel work for 10 years)								

Table 50.   Aegis O&S Costs

Table 51 lists the values used to derive the disposal costs for the Aegis ships component. These activities were used to estimate the costs to dismantle and dispose of the Aegis ships and what type of work/personnel was included in the accounting.

Program Activity	Year 11	Estimate Totals	Notes
Government			
Program Engineer	$89,846	$89,846	1 GS-12
Support Personnel	$120,000	$120,000	5 E-4s@$24k
Support Equipment	$150,000	$150,000	
Facilities	$7,000	$7,000	
Contractor			
Support Personnel	$120,000	$120,000	5 E-4s@$24k
Support Equipment		$0	
Technical Data	$70,000	$70,000	1 Employee@$70k
Transportation and Handling	$150,000	$150,000	
Total Disposal Costs	$706,846	$706,846	

Table 51.   Aegis Disposal Costs

Table 52 was used to derive the R&D costs for the THAAD component. The years were staggered to reflect the length of time for the respective phase of the component development to commence, complete, and enter the next development phase, keeping in mind that all components saw identical phases and a 10-year life span.

Program Activity	Year 1	Year 2	Estimate Totals	Notes
Government				
System Management	$136,771	$142,241	$279,012	1 GS14
Systems Engineering	$415,742	$432,372	$848,114	1 GS13, 2 GS12s
Product Research & Design	$150,000	$156,000	$306,000	2 GS12s
System T&E	$150,000	$156,000	$306,000	2 GS12s
Contractor				
System Management	$140,000	$145,600	$285,600	
Product Research, Planning, and Design	$14,836,900	$15,430,376	$30,267,276	1 THAAD Battery & Trade Techs/($50/hr)
System Documentation	$70,000	$72,800	$142,800	1 Employee @ $70k
System T&E	$350,000	$364,000	$714,000	2 Employees @ $70k (Contractor will determine personnel, estimate will be adjusted according to contractor's proposal)
Total R&D Costs	$16,249,413	$16,899,389	$33,148,802	

Table 52.   THAAD R&D Costs

Table 53 lists the values used to derive the production and construction costs for the THAAD component.

Program Activity	Year			Estimate Totals	Notes
	2	3	4		
Government					
System Management	$137,771	$143,281	$149,013	$430,065	1 GS14
Contractor					
System Management	$130,000	$135,200	$140,608	$405,808	
Manufacturing					
Recurring Costs	$614,307,000	$638,879,280	$664,434,451	$1,917,620,731	Assuming 48 interceptors/yr,
Nonrecurring Costs	$15,000,000			$15,000,000	1 THAAD Battery
Quality Control	$124,000	$128,960	$134,118	$387,078	1 QA
Initial Logistical Support					
Supply Support	$95,847,000	$99,680,880		$195,527,880	6 Launchers & 1 Tact Station Group
Transportation and Handling	$150,000			$150,000	Shipping and Handling
Technical Data	$87,000	$90,480	$94,099	$271,579	
Personnel and Training	$9,442,000	$9,819,680		$19,261,680	
Total P&C Costs	$735,224,771	$748,877,761	$664,952,289	$2,149,054,822	

Table 53.   THAAD Production and Construction Costs

Table 54 lists the values used to derive the O&S costs for the THAAD component. These activities were used to estimate the costs to operate and provide operational support for the THAAD and what type of work/personnel was including in the accounting.

Program Activity	Year								Estimate Totals
	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	
Government									
System Management[1]	$137,771	$143,281	$149,013	$154,973	$161,172	$167,619	$174,324	$181,297	$1,269,453
Operating Personnel[2]	$530,640	$551,866	$573,940	$596,898	$620,774	$645,605	$671,429	$698,286	$4,889,437
Unscheduled Maintenance[3]	$130,000	$135,200	$140,608	$146,232	$152,081	$158,164	$164,491	$171,071	$1,197,849
Maintenance Facilities	$25,000	$26,000	$27,040	$28,121	$29,246	$30,416	$31,632	$32,898	$230,355
Supply Support[4]			$691,011,829	$718,652,302	$747,398,394	$777,294,330	$808,386,103	$840,721,547	$4,583,464,507
Maintenance Personnel Training[5]	$9,442,000	$9,819,680	$10,212,467	$10,620,965	$11,045,804	$11,487,636	$11,947,142	$12,425,027	$87,000,724
Test and Support Equipment	$1,927,000	$2,004,080	$2,084,243	$2,167,612	$2,254,317	$2,344,490	$2,438,269	$2,535,800	$17,755,814
Transportation and Handling	$150,000								$150,000.
Total O&S Costs	$12,342,411	$12,680,107	$704,199,141	$732,367,107	$761,661,791	$792,128,263	$823,813,393	$856,765,929	$4,695,958,141
Notes									
1	1 GS14								
2	1 THAAD Crew (20 personnel) (Sources: http://www.military-today.com/missiles/thaad.htm, http://www.fas.org/spp/starwars/docops/fm44–100–2fd/chapter4.htm,http://www.militaryfactory.com/military_pay_scale.asp) Costs include 18 E-4s@$24972, 1 E-5@$28980 and 1 O-2@$52164.								
3	General PM performed								
4	Assuming 29 Interceptors/yr, SM-3 BlkIB								
5	10 Personnel @ $45k ea (Personnel work for 10 years)								

Table 54.   THAAD O&S Costs

Table 55 lists the values used to derive the disposal costs for the THAAD component. These activities were used to estimate the costs to dismantle and dispose of the THAAD and what type of work/personnel was included in the accounting.

Program Activity	Year 11	Estimate Totals	
Government			
Program Engineer	$89,846	$89,846	1 GS-12
Support Personnel	$120,000	$120,000	5 E-4s@$24k
Support Equipment	$30,000	$30,000	
Facilities	$20,000	$20,000	
Contractor			
Support Personnel	$120,000	$120,000	5 E-4s@$24k
Support Equipment		$0.00	
Technical Data	$70,000	$70,000	1 Employee @ $70k
Transportation and Handling	$150,000	$150,000	
Total Disposal Costs	$599,846	$599,846	

Table 55. THAAD Disposal Costs

Table 56 was used to derive the R&D costs for the AN/TPY-2 component. The years were staggered to reflect the length of time for the respective phase of the component development to commence, complete, and enter the next development phase, keeping in mind that all components saw identical phases and a 10-year life span.

Program Activity	Year 1	Year 2	Estimate Totals	Notes
Government				
System Management	$136,771	$142,241	$279,012	1 GS14
Systems Engineering	$415,742	$432,372	$848,114	1 GS13, 2 GS12s
Product Research & Design	$150,000	$156,000	$306,000	2 GS12s
System T&E	$150,000	$156,000	$306,000	2 GS12s
Contractor				
System Management	$140,000	$145,600	$285,600	
Product Research, Planning, and Design	$347,000,000	$360,880,000	$707,880,000	1 AN/TPY-2/yr
System Documentation	$70,000	$72,800	$142,800	1 Employee@$70k
System T&E	$140,000	$145,600	$285,600	2 Employees@$70k (Contractor will determine personnel, estimate will be adjusted according to contractor's proposal)
Total R&D Costs	$348,202,513	$362,130,613	$710,333,126	

Table 56. AN/TPY-2 R&D Costs

Table 57 lists the values used to derive the production and construction costs for the AN/TPY-2 component. These activities were used to estimate the costs to build the AN/TPY-2 and what type of logistical effort is required.

Program Activity	Year			Estimate Totals	Notes
	2	3	4		
Government					
System Management	$137,771	$143,281	$149,013	$430,065	1 GS14
Contractor					
System Management	$130,000	$135,200	$140,608	$405,808	
Manufacturing					
Recurring Costs	$10,000,000	$10,400,000	$10,816,000	$31,216,000	Assuming 1 spare/yr,
Nonrecurring Costs	$217,244,000			$217,244,000	1 AN/TPY-2 Radar
Quality Control	$124,000	$128,960	$134,118	$387,078	1 QA
Initial Logistical Support					
Supply Support	$73,940,000			$73,940,000	Cooling Equipment Unit, Electronic Equipment Units, Forward-Based Mode Prime Power Units, Prime Power Units X2/Radar
Transportation and Handling	$150,000	$156,000	$162,240	$468,240	Shipping and Handling
Technical Data	$87,000	$90,480	$94,099	$271,579	
Personnel, Equipment, and Training	$1,040,000			$1,040,000	
Total P&C Costs	$302,852,771	$11,053,921	$11,496,078	$325,402,771	

Table 57.   AN/TPY-2 Production and Construction Costs

Table 58 lists the values used to derive the O&S costs for the AN/TPY-2 component. These activities were used to estimate the costs to operate and provide operational support for the AN/TPY-2 and what type of work/personnel was including in the accounting.

Program Activity	Year 3	4	5	6	7	8	9	10	Estimate Totals
Government									
System Management[1]	$137,771	$143,281	$149,013	$154,973	$161,172	$167,619	$174,324	$181,297	$1,269,453
Operating Personnel[2]	$1,080,024	$1,123,225	$1,168,154	$1,214,880	$1,263,475	$1,314,014	$1,366,575	$1,421,238	$9,951,586
Unscheduled Maintenance	$100,000	$104,000	$104,000	$108,160	$108,160	$112,486	$112,486	$116,985	$866,278
Maintenance Facilities[3]	$25,000	$26,000	$26,000	$27,040	$27,040	$28,121	$28,121	$29,246	$216,569
Supply Support[4]		$73,940,000							$73,940,000
Maintenance Personnel Training[5]	$90,000	$93,600	$93,600	$97,344	$97,344	$101,237	$101,237	$105,287	$779,650
Test and Support Equipment	$1,000,000				$350,000				$1,350,000
Transport and Handling	$150,000								$150,000
Total O&S Costs	$2,582,795	$75,430,107	$1,540,767	$1,602,398	$2,007,192	$1,723,480	$1,782,745	$1,854,055	$88,523,538
Notes:									
1	1 GS14								
2	1 AN/TPY-2 Crew (Source: http://www.dfas.mil/militarymembers/payentilements/militarypaytables.html http://www.fas.org/spp/starwars/docops/fm44–100–2fd/chapter4.htm,http://www.militaryfactory.com/military_pay_scale.asp) Costs include 40 E-4s@$24972, 1 E-5@$28980 and 1 O-2@$52164.								
3	General PM performed								
4	The following equipment must be purchased to maintain operational capability through the 10-year life cycle: Cooling Equipment Unit, Electronic Equipment Units, Forward-Based Mode Prime Power Units, Prime Power Units X2/Radar. This occurs only in year 4 because that is when it contractually obligated to be completely built. According to MDA Procurement Budget.								
5	10 Personnel @ $45k ea (Personnel work for 10 years)								

Table 58.   AN/TPY-2 O&S Costs

Table 59 lists the values used to derive the disposal costs for the AN/TPY-2 component. These activities were used to estimate the costs to dismantle and dispose of the AN/TPY-2 and what type of work/personnel was included in the accounting.

Program Activity	Year 11	Estimate Totals	Notes
Government			
Program Engineer	$89,846	$89,846	1 GS-12
Support Personnel	$120,000	$120,000	5 E-4s@$24k
Support Equipment	$150,000	$150,000	
Facilities	$25,000	$25,000	
Contractor			
Support Personnel	$120,000	$120,000	5 E-4s@$24k
Support Equipment		$0.00	
Technical Data	$70,000	$70,000	1 Employee@$70k
Transportation and Handling	$150,000	$150,000	
Total Disposal Costs	$724,846	$724,846	

Table 59.   THAAD Disposal Costs

Table 60 was used to derive the R&D costs for the PAC-3 component. The years were staggered to reflect the length of time for the respective phase of the component development to commence, complete, and enter the next development phase, keeping in mind that all components saw identical phases and a 10-year life span.

Program Activity	Year 1	Year 2	Estimate Totals	Notes
Government				
System Management	$136,771	$142,241	$279,012	1 GS14
Systems Engineering	$415,742	$432,372	$848,114	1 GS13, 2 GS12s
Product Research & Design	$150,000	$156,000	$306,000	2 GS12s
System T&E	$150,000	$156,000	$306,000	2 GS12s
Contractor				
System Management	$140,000	$145,600	$285,600	
Product Research, Planning, and Design	$33,000,000	$34,320,000	$67,320,000	1 PAC-3 Battery & Trade Techs/($50/hr)
System Documentation	$70,000	$72,800	$142,800	1 Employee @ $70k
System T&E	$140,000	$145,600	$285,600	2 Employees @ $70k (Contractor will determine personnel, estimate will be adjusted according to contractor's proposal)
Total R&D Costs	$34,202,513	$35,570,613	$69,773,126	

Table 60.　　　PAC-3 R&D Costs

Table 61 lists the values used to derive the production and construction costs for the PAC-3 component. These activities were used to estimate the costs to build the PAC-3 and what type of work/personnel was included in the accounting.

Program Activity	Year			Estimate Totals	Notes
	2	3	4		
Government					
System Management	$137,771	$143,281	$149,013	$430,065	1 GS14
Contractor					
System Management	$130,000	$135,200	$140,608	$405,808	
Manufacturing					
Recurring Costs	$323,100,000	$336,024,000	$349,464,960	$1,008,588,960	Assuming 84 interceptors/yr, PAC-3
Nonrecurring Costs	$3,000,000			$3,000,000	1 PAC-3 Battery
Quality Control	$124,000	$128,960	$134,118	$387,078	1 QA
Initial Logistical Support					
Supply Support	$2,800,000	$2,912,000		$5,712,000	1 PAC-3 & 1 Tact Station Group
Transportation and Handling	$150,000			$150,000	Shipping and Handling
Technical Data	$87,000	$90,480	$94,099	$271,579	
Personnel and Training	$9,442,000	$9,819,680		$19,261,680	
Total P&C Costs	$338,970,771	$349,253,601	$349,982,798	$1,038,207,171	

Table 61.　　　PAC-3 Production and Construction Costs

Table 62 lists the values used to derive the O&S costs for the PAC-3 component. These activities were used to estimate the costs to operate and provide operational support for the PAC-3 and what type of work/personnel was including in the accounting.

Program Activity	Year								Estimate Totals
	3	4	5	6	7	8	9	10	
Government									
System Management[1]	$137,771	$143,281	$149,013	$154,973	$161,172	$167,619	$174,324	$181,297	$1,269,453
Operating Personnel[2]	$2,282,688	$2,373,996	$2,468,955	$2,567,714	$2,670,422	$2,777,239	$2,888,329	3,003,862	$21,033,204
Unscheduled Maintenance[3]	$130,000	$135,200	$140,608	$146,232	$152,081	$158,164	$164,491	$171,071	$1,197,849
Maintenance Facilities	$15,000	$15,600	$16,224	$16,872	$17,547	$18,249	$18,979	$19,738	$138,213
Supply Support[4]			$363,443,558	$377,981,300	$393,100,552	$408,824,574	$425,177,557	$442,184,660	$2,410,712,204
Maintenance Personnel Training[5]	$9,442,000	$9,819,680	$10,212,467	$10,620,965	$11,045,804	$11,487,636	$11,947,142	$12,425,027	$87,000,724
Test and Support Equipment	$1,927,000	$2,004,080							$3,931,080
Transportation and Handling	$150,000								$150,000
Total O&S Costs	$14,084,459	$14,491,837	$376,430,826	$391,488,059	407,147,581	423,433,485	440,370,824	$457,985,657	$2,525,432,729
Notes									
1	1 GS14								
2	1 PAC-3 Crew (90 personnel) (Sources: http://www.dfas.mil/militarymembers/payentilements/militarypaytables.html ,http://www.globalsecurity.org/space/library/policy/army/fm/3–01–85/appb.htm, http://www.militaryfactory.com/military_pay_scale.asp), http://tech.military.com/equipment/view/88751/patriot-missile.html Costs include 87 E-4s@$24972, 2 E-5s@$28980 and 1 O-2@$52164.								
3	General PM performed								
4	Assuming 84 Interceptors/yr, PAC-3								
5	10 Personnel @ $45k ea (Personnel work for 10 years)								

Table 62.   PAC-3 O&S Costs

Table 63 lists the values used to derive the disposal costs for the PAC-3 component. These activities were used to estimate the costs to dismantle and dispose of the PAC-3 and what type of work/personnel was included in the accounting.

Program Activity	Year 11	Estimate Totals	Notes
Government			
Program Engineer	$89,846	$89,846	1 GS-12
Support Personnel	$120,000	$120,000	5 E-4s@$24k
Support Equipment	$30,000	$30,000	
Facilities	$20,000	$20,000	
Contractor			
Support Personnel	$120,000	$120,000	5 E-4s@$24k
Support Equipment			
Technical Data	$70,000	$70,000	1 Employee@$70k
Transportation and Handling	$150,000	$150,000	
Total Disposal Costs	$599,846	$599,846	

Table 63.   PAC-3 Disposal Costs

Table 64 lists the year-to-year breakdown of EBMD Alternative costs in billions.

Year	EBMD Alternative					
	Baseline	**A**	**B.1**	**B.2**	**B.3**	**C**
1	$0.61	$0.46	$0.47	$0.49	$0.51	$0.40
2	$3.46	$1.77	$2.52	$3.27	$4.02	$1.22
3	$2.60	$0.83	$1.59	$2.36	$3.12	$0.42
4	$2.69	$0.94	$1.61	$2.29	$2.97	$0.51
5	$2.69	$0.88	$1.59	$2.29	$3.00	$0.44
6	$2.80	$0.92	$1.65	$2.38	$3.11	$0.46
7	$2.91	$0.96	$1.72	$2.48	$3.24	$0.48
8	$3.03	$0.99	$1.79	$2.58	$3.37	$0.50
9	$3.15	$1.04	$1.86	$2.69	$3.51	$0.52
10	$3.28	$1.08	$1.93	$2.79	$3.65	$0.54
Total	$27.37	$10.01	$16.87	$23.77	$30.64	$5.49

Table 64.   EBMD Alternative Year to Year Breakdown Costs in Billions

Table 65 through Table 70 list the costs per EBMD Alternative, with the EBMD Alternatives being broken down into their components.

Program Activity	Component		
	1 Aegis	**AN/TPY-2**	**6 PAC-3**
Total R&D Costs	$111,470,727	$710,333,127	$418,638,759
Total P&C Costs	$1,322,766,392	$325,402,772	$6,229,243,029
Total O&S Costs	$3,008,040,385	$86,523,538	$15,152,596,373
Total Disposal Costs	$1,413,692	$724,846	$3,599,076
Component Total	$4,443,691,196	$1,123,984,282	$21,804,077,238
Total	$27,372,752,716		

Table 65.   Total Cost of the Baseline

Program Activity	Component	
	2 Aegis	**1 AN/TPY-2**
Total R&D Costs	$222,941,453	$710,333,127
Total P&C Costs	$2,645,532,785	$325,402,772
Total O&S Costs	$6,016,080,771	$86,523,538
Total Disposal Costs	$1,413,692	$724,846
Component Total	$8,885,968,701	$1,123,984,282
Total	$10,010,952,982	

Table 66.   Total Cost of Alternative A

Program Activity	Component		
	2 Aegis	**1 AN/TPY-2**	**1 THAAD**
Total R&D Costs	$222,941,453	$710,333,127	$33,148,803
Total P&C Costs	$2,645,532,785	$325,402,772	$2,149,054,823
Total O&S Costs	$6,016,080,771	$86,523,538	$4,695,958,141
Total Disposal Costs	$1,413,692	$724,846	$599,846
Component Total	$8,885,968,701	$1,123,984,282	$6,878,761,613
Total	$16,889,714,595		

Table 67.   Total Cost of Alternative B.1

Program Activity	Component		
	2 Aegis	**1 AN/TPY-2**	**2 THAAD**
Total R&D Costs	$222,941,453	$710,333,127	$66,297,605
Total P&C Costs	$2,645,532,785	$325,402,772	$4,298,109,646
Total O&S Costs	$6,016,080,771	$86,523,538	$9,391,916,282
Total Disposal Costs	$1,413,692	$724,846	$1,199,692
Component Total	$8,885,968,701	$1,123,984,282	$13,757,523,225
Total	$23,768,476,208		

Table 68.   Total Cost of Alternative B.2

Program Activity	Component		
	2 Aegis	**1 AN/TPY-2**	**3 THAAD**
Total R&D Costs	$222,941,453	$710,333,127	$99,446,408
Total P&C Costs	$2,645,532,785	$325,402,772	$6,447,164,468
Total O&S Costs	$6,016,080,771	$86,523,538	$14,087,874,424
Total Disposal Costs	$1,413,692	$724,846	$1,799,538
Component Total	$8,885,968,701	$1,123,984,282	$20,636,284,838
Total	$30,647,237,820		

Table 69.   Total Cost of Alternative B.3

Program Activity	Component	
	1 Aegis Ashore	**1 AN/TPY-2**
Total R&D Costs	$111,470,727	$710,333,127
Total P&C Costs	$1,322,385,720	$325,402,772
Total O&S Costs	$2,933,942,581	$86,523,538
Total Disposal Costs	$431,846	$724,846
Component Total	$4,368,230,874	$1,123,984,282
Total	$5,493,215,156	

Table 70.   Total Cost of Alternative C

Table 71 lists the year-to-year breakdown of EBMD Alternative costs in billions.

Year	EBMD Alternative					
	Baseline	A	B.1	B.2	B.3	C
1	$0.61	$0.46	$0.47	$0.49	$0.51	$0.40
2	$3.46	$1.77	$2.52	$3.27	$4.02	$1.22
3	$2.60	$0.83	$1.59	$2.36	$3.12	$0.42
4	$2.69	$0.94	$1.61	$2.29	$2.97	$0.51
5	$2.69	$0.88	$1.59	$2.29	$3.00	$0.44
6	$2.80	$0.92	$1.65	$2.38	$3.11	$0.46
7	$2.91	$0.96	$1.72	$2.48	$3.24	$0.48
8	$3.03	$0.99	$1.79	$2.58	$3.37	$0.50
9	$3.15	$1.04	$1.86	$2.69	$3.51	$0.52
10	$3.28	$1.08	$1.93	$2.79	$3.65	$0.54
Total	$27.37	$10.01	$16.87	$23.77	$30.64	$5.49

Table 71.   EBMD Alternative Year-to-Year Breakdown Costs in Billions

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APPENDIX E. ANALYSIS OF ALTERNATIVES DATA

Table 72 lists the raw and processed data used in support of establishing comparison plots for life cycle cost as well as comparative percentage values.

Program Activity	Cost, $					
	C	B.3	B.2	B.1	A	Baseline
R&D	$821,803,853	$1,032,720,987	$999,572,185	$966,423,382	$933,274,580	$1,240,442,612
P&C	$1,647,788,492	$9,418,100,025	$7,269,045,202	$5,119,990,379	$2,970,935,556	$7,877,412,193
O&S	$3,022,466,119	$20,192,478,732	$15,496,520,591	$10,800,562,450	$6,104,604,309	$18,249,160,296
Disposal	$1,156,692	$3,938,076	$3,338,230	$2,738,384	$2,138,538	$5,030,768
Total	$5,493,215,156	$30,647,237,820	$23,768,476,208	$16,889,714,595	$10,010,952,982	$27,372,045,870
R&D	15%	3%	4%	6%	9%	5%
P&C	30%	31%	31%	30%	30%	29%
O&S	55%	66%	65%	64%	61%	67%
Disposal	0%	0%	0%	0%	0%	0%
	C	B.3	B.2	B.1	A	Baseline
Lower than Baseline	80%	-12%	13%	38%	63%	0%
Percentage of Baseline	20%	112%	87%	62%	37%	100%

Table 72.   Data Used to Evaluate Life-Cycle Costs in Billions

Table 73 lists supporting performance and cost data for populating the evaluation measure plots and decision evaluation display.

Evaluation Measure	EBMD Alternative					
	Baseline	A	B.1	B.2	B.3	C
Probability of Intercept	0.614	0.676	0.780	0.869	0.905	0.714
Percent Footprint Defended	70.1%	76.1%	89.8%	96.6%	100%	100%
Total Cost (Billions)	$27.37	$10.01	$16.89	$23.77	$30.65	$5.49

Table 73.   Data Used for Calculating the Decision Evaluation Display

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LIST OF REFERENCES

Analytical Graphics Incorporated. 2013. *STK/Missile Modeling Tools.*
    http://www.agi.com/downloads/partners/business/resources/MMT_flyer.pdf.

Arms Control Association. 2012. *Fact Sheets And Briefs.* Accessed November 8, 2012.
    http://www.armscontrol.org/factsheets/missiles.

Army Recognition. 2013. *AN/MPQ-53 multifunction phased-array radar Patriot MIM-
    104.* Accessed April 4, 2013. http://www.armyrecognition.com/patriot_mim-
    104_vehicles_systems_us_army_uk/an_mpq-53_patriot_radar_search_detection_
    illumination_data_sheet_specifications_information_uk.html.

Blanchard, Benjamin S. and Wolter J. Fabrycky. 2011. *Systems Engineering and
    Analysis,* 5th ed. Upper Saddle River, NJ: Prentice Hall.
    http://www.amazon.com/Engineering-Analysis-Prentice-International-
    Industrial/dp/013221735X.

Butler, Rhett. 2009. *Cities And Urban Areas In Turkey With Population Over 100,000.*
    Accessed May 29, 2013. http://www.mongabay.com/igapo/Turkey.htm.

Cappacio, Tony. 2012. "Iran's Ballistic Missiles Improving, Pentagon Finds." July 10.
    http://www.bloomberg.com/news/2012–07–10/iran-improves-ballistics-missiles-
    to-target-ships.html.

Cepak, Commander Robert J. 2005. *Ground Based Midcourse Defense: Continue
    Testing, But Operational Fielding Must Take A Backseat to Theater Missile
    Defense And Homeland Security.* Norfolk: Joint Forces Staff College Joint
    Advance Warfighting School. http://www.dtic.mil/dtic/tr/fulltext/u2/a436540.pdf.

Coffey, Luke. 2012. *Keeping America Safe Why U.S. Bases In Europe Remain Vital.* The
    Heritage Foundation. http://thf_media.s3.amazonaws.com/2012/pdf/SR111.pdf.

DDC-I. 2013. *The Mk 41 Vertical Launching System Depends on DACS.* Accessed May
    3, 2013. http://www.ddci.com/displayNews.php?fn=programs_vls.php.

Deagel.com. 2013. *Standard SM-3 Block IA.* February. Accessed May 4, 2013.
    http://www.deagel.com/Anti-Ballistic-Missiles/Standard-SM-3-Block-
    IA_a001148009.aspx.

Defense Industry Daily. 2013a. *Serious Dollars for AEGIS Ballistic Missile Defense
    Modifications (BMD).* May 23. https://www.defenseindustrydaily.com/serious-
    dollars-for-aegis-ballistic-missile-defense-modifications-03091/.

Defense Industry Daily. 2013b. *AN/TPY-2: America's Portable Missile Defense Radar.*
March 19. http://www.defenseindustrydaily.com/antpy-2-ground-radar-07533/.

Deputy Secretary of Defense. 2009. "DoD Directive 5134.09." *DTIC.*
http://www.dtic.mil/whs/directives/corres/pdf/513409p.pdf.

Elleman, Michael. 2012. *Iran's Ballistic Missile Program.*
http://iranprimer.usip.org/resource/irans-ballistic-missile-program.

Encyclopedia Astronautica. 2011a. *Standard SM-3.*
http://www.astronautix.com/lvs/stardsm3.htm.

Encyclopedia Astronautica. 2011b. *THAAD.*
http://www.astronautix.com/lvs/thaad.htm

Federation of American Scientists. 1999a. *MK 36 SRBOC.*
http://www.fas.org/man/dod-101/sys/ship/weaps/mk-36.htm.

Federation of American Scientists. 1999b. *AN/SLQ-32 Electronic Warfare system.*
http://www.fas.org/man/dod-101/sys/ship/weaps/an-slq-32.htm.

Federation of American Scientists. 2000a. *Ballistic Missile Basics.*
http://www.fas.org/nuke/intro/missile/basics.htm.

Federation of American Scientists. 2000b. *Patriot TMD.*
http://www.fas.org/spp/starwars/program/patriot.htm.

Federation of American Scientists. 2008. *Shahab-3 / Zelzal-3.*
http://www.fas.org/programs/ssp/man/militarysumfolder/shahab-3.html.

Free Software Foundation, Inc. 2011. *Bash Reference Manual.*
http://www.gnu.org/software/bash/manual/bashref.html.

Gansler, Jacques S. 2010. *Ballistic Missile Defense Past And Future.* Washington, DC:
Center For Technology And National Security Policy National Defense
University. http://www.ndu.edu/CTNSP/docUploaded/BMD_2010.pdf.

Geobytes. 2010. *City Distance Tool.*
http://www.geobytes.com/CityDistanceTool.htm?loadpage

GAO. 2010. "Missile Defense: European Phased Adaptive Approach Acquisitions Face
Synchronization, Transparency, and Accountability Challenges." *GAO.*
http://www.gao.gov/new.items/d11179r.pdf.

GAO. 2011. *DoD Needs to Address Planning and Implementation Challenges for Future Capabilities in Europe.* Washington, DC: Government Accountability Office. http://www.gao.gov/assets/320/315170.pdf.

George C. Marshall and Claremont Institutes. 2013a. *Missiles of the World.* http://missilethreat.com/missiles-of-the-world/.

George C. Marshall and Claremont Institutes. 2013b. *Shahab-3*. http://missilethreat.com/missiles/shahab-3/.

George C. Marshall and Claremont Institutes. 2013c. *Sejil 1/2/3*. http://missilethreat.com/missiles/sejil-123/?country=iran#iran.

George C. Marshall and Claremont Institutes. 2012d. *Range, Accuracy and Warheads.* November. http://missilethreat.com/range-accuracy-and-warheads/.

Hildreth, Steven A. 2009. *Iran's Ballistic Missile Programs: An Overview.* CRS Report 22758. Library of Congress, Congressional Research Service, Washington, DC.

Hildreth, Steven A. 2012. *Iran's Ballistic Missile and Space Launch Programs.* CRS Report R42849. Congressional Research Service, Washington, DC. http://www.fas.org/sgp/crs/nuke/R42849.pdf.

IHS Janes. 2001. *Aegis weapon system MK-7*. http://web.archive.org/web/20060701055247/http://www.janes.com/defence/naval_forces/news/misc/aegis010425.shtml.

IHS Janes. 2012. *Standard Missile 1/2/3/5/6 (RIM-66/67/156/161/165/174)*. https://janes.ihs.com.libproxy.nps.edu/CustomPages/Janes/DisplayPage.aspx?DocType=Reference&ItemId=+++1499726&Pubabbrev=JNW_#Standard%20Missile%203%20%28SM-3%29.

IHS Janes. 2013. *PAC-3*. https://libproxy.nps.edu/login?url=https://janes.ihs.com/CustomPages/Janes/DisplayPage.aspx?DocType=Reference&ItemId=+++1363354&Pubabbrev=JLAD.

Jeremiah D. Sullivano, Dan Fenstermacherb, Daniel Fisher, Ruth Howesd, O'Dean Judde, Roger Speed. 1999. "Technical Debate over Patriot Performance in the Gulf War." *Science & Global Security* (Overseas Publishers Association) 8: 41–98. http://www.princeton.edu/sgs/publications/sgs/pdf/8_1sullivan.pdf.

Lewis, George, and Theodore Postol. 1992. "Review of Army's Study on Patriot Effectiveness." *Inside The Army* 12. http://www.fas.org/spp/starwars/docops/pl920908.htm.

Lewis, George, and Theodore Postol. 2012a. *Ballistic Missile Defense: Estimating the Range of an Aegis Radar against a Missile Warhead Target.* October 23. http://mostlymissiledefense.com/2012/10/23/438/.

Lewis, George, and Theodore Postol. 2012b. *Ballistic Missile Defense: Radar Range Calculations for the AN/TPY-2 X-Band and NAS Proposed GBX Radars.* September 21. http://mostlymissiledefense.com/2012/09/21/ballistic-missile-defense-radar-range-calculations-for-the-antpy-2-x-band-and-nas-proposed-gbx-radars-september-21–2012/.

Mantle, Peter J. 2004. *The Missile Defense Equation: Factors for Decision Making.* Reston, VA: American Institute of Aeronautics and Astronautics. http://www.amazon.com/Missile-Defense-Equation-Library-Flight/dp/1563476096.

Missile Defense Agency. 2007. *MDA Conducts Successful Rocket Motor Test for Kinetic Energy.* Washington, DC: Missile Defense Agency. http://www.mda.mil/global/documents/pdf/07news0045.pdf.

Missile Defense Agency. 2011. *The Missile Defense Agency Program Update.* Washington, DC: Missile Defense Agency. http://www.mda.mil/global/documents/pdf/The_Missile_Defense_Program.pdf.

Missile Defense Agency. 2012a. "European Phased Adaptive Approach (EPAA) Ballistic Missile Defense." Washington, DC. http://photos.state.gov/libraries/russia/231771/PDFs/EPAA%20Technical%20Overview%20ENG.pdf.

Missile Defense Agency. 2012b. *The Threat.* http://www.mda.mil/system/threat.html.

Missile Defense Agency. 2012c. *PAA Mission.* www.mda.mil/system/paa.html.

Missile Defense Agency. 2013a. "A System of Elements." *Missile Defense Agency.* January. http://www.mda.mil/system/elements.html.

Missile Defense Agency. 2013b. *Aegis Ashore.* http://www.mda.mil/system/aegis_ashore.html.

Missile Defense Agency. 2013c. *Aegis Ballistic Missile Defense.* http://www.mda.mil/system/aegis_bmd.html.

Missile Defense Agency. 2013d. *News Releases.* http://www.mda.mil/news/news_releases.html.

Missile Defense Agency. 2013e. *The Ballistic Missile Defense System (BMDS).* http://www.mda.mil/system/system.html.

Missile Defense Agency. 2013f. "PAC-3 Factsheet."
	http://www.mda.mil/global/documents/pdf/pac3.pdf.

Missile Defense Agency. 2013g. "THAAD Fact Sheet."
	http://www.mda.mil/global/documents/pdf/thaad.pdf.

Missile Defense Agency. 2013h. "Aegis Fact Sheet."
	http://www.mda.mil/global/documents/pdf/aegis.pdf.

Missile Defense Agency. 2013i. "Army Navy / Transportable Radar Surveillance
	(AN/TPY-2)." *Missile Defense Agency.*
	http://www.mda.mil/global/documents/pdf/an_tpy2.pdf.

Missile Defense Agency. 2013j. "Space Tracking and Surveillance System." *Missile
	Defense Agency.* http://www.mda.mil/global/documents/pdf/stss.pdf.

Missile Defense Agency. 2013k. "Sea-Based X-Band Radar." *Missile Defense Agency.*
	http://www.mda.mil/global/documents/pdf/sbx.pdf.

Missile Defense Agency. 2013l. "Upgraded Early Warning Radars, AN/FPS-132."
	Missile Defense Agency. http://www.mda.mil/global/documents/pdf/uewr1.pdf.

NAVSEA. 2012a. *Aegis Technical Representative.*
	http://www.navsea.navy.mil/aegistechrep.aspx.

NAVSEA. 2012b. *Program Executive Office, Ships.*
	http://www.navsea.navy.mil/teamships/teamships/PEOShips.aspx.

North Atlantic Treaty Organization. 2013. *All NATO Patriot Batteries in Turkey
	Operational.* http://www.nato.int/cps/en/natolive/news_98494.htm.

The Nuclear Threat Initiative. 2011a. Imam Ali Missile Base.
	http://www.nti.org/facilities/308/.

The Nuclear Threat Initiative. 2011b. Tabriz Missile Base.
	http://www.nti.org/facilities/316/.

The Nuclear Threat Initiative. 2013. Iran Delivery Systems. February.
	http://www.nti.org/country-profiles/iran/delivery-systems/.

Office of the Director, Defense Research and Engineering, DoD. 2010. *Systems
	Engineering Guide for Systems of Systems.* Washington, DC: Director of Systems
	Engineering, Office of the Director, Defense Research and Engineering.
	http://www.acq.osd.mil/se/docs/SoS-Summary-PRINT.Format-
	Duplex.FlipUp.pdf.

Office of the Under Secretary of Defense for Policy. 2012. *Deputy Assistant Secretary of Defense for Nuclear and Missile Defense Policy.* http://policy.defense.gov/OUSDPOffices/ASDforGlobalStrategicAffairs/NuclearMissileDefensePolicy.aspx.

Office of the Under Secretary of Defense. 2012. "United States Department of Defense Fiscal Year 2013 Budget Request." http://comptroller.defense.gov/defbudget/fy2013/FY2013_Budget_Request_Overview_Book.pdf.

O'Reilly, LTG Patrick J. 2011. *Ballistic Missile Defense Overview.* Apr 26. http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&ved=0CC4QFjAA&url=http%3A%2F%2Fwww.ausaredstone.org%2Ffiles%2F2011%2FLTG%2520Patrick%2520OReilly%2520Speaker%2520Briefing_AUSA%2520Missiles%2520Conferen.pdf&ei=_B6YUcCRB6vOigKW8IGAAw&u.

O'Rourke, Ronald. 2010. "Navy Aegis Ballistic Missile Defense (BMD) Program: Background and Issues for Congress." http://fpc.state.gov/documents/organization/142710.pdf.

O'Rourke, Ronald. 2013. "Navy Aegis Ballistic Missile Defense (BMD) Program: Background and Issues for Congress." http://www.fas.org/sgp/crs/weapons/RL33745.pdf.

Postol, Theodore. 2009. *A Technical Assessment of Iran's Ballistic Missile Program.* EastWest Institute, Washington, DC: EastWest Institute. http://docs.ewi.info/JTA_TA_Program.pdf.

Secretary of Defense. 2010. *Ballistic Missile Defense Review Report.* Washington, DC: Secretary of Defense. http://www.defense.gov/bmdr/docs/BMDR%20as%20of%2026JAN10%200630_for%20web.pdf.

Senate Committee on Armed Services. 2012. "Statement of General C.R. Kehler Command United States Strategic Command Before the Senate Committee on Armed Services." *U.S. Strategic Command.* http://www.stratcom.mil/files/2012_Posture_Statement.pdf.

Shirzad Bozorgmehr, Pam Benson, Charley Keyes, Barbara Starr. 2009. *Iran tests new surface-to-surface missile.* http://www.cnn.com/2009/WORLD/meast/05/20/iran.missile.test/.

Simon, Alexander. 1996. *The Patriot Missile. Performance in the Gulf War Reviewed.* http://www.gulflink.osd.mil/scud_info/scud_info_refs/n41en141/Patriot.html.

U.S. Department of Defense. 2004. *How Missile Defense Works.* http://www.defense.gov/specials/missiledefense/nmd.html.

Under Secretary of Defense . 2010. "Report to Congress on Assessment of the Ground-Based Mid course Defense Element of the Ballistic Missile Defense System." http://www.dod.mil/pubs/foi/homeland_defense/missile_defense_agency/10_F_1 399Report_toCongress_onAssessment_of_the_GBMD_Element_of_the_BMDS.p df.

United States European Command. 2012a. *EUCOM Mission.* http://www.eucom.mil/mission.

United States European Command. 2012b. "EUCOM 2012 Posture Statement." *United States European Command.* http://www.eucom.mil/doc/23162/2012-high-res-posture-statement.pdf.

United States Strategic Command. 2011. *STRATCOM Mission.* April. http://www.stratcom.mil/mission/.

Vitech Corporation. 2013. *CORE.* http://www.vitechcorp.com /products/core.shtml.

White House. 2012. *Fact Sheet: Chicago Summit – NATO Capabilities.* http://www.whitehouse.gov/the-press-office/2012/05/20/fact-sheet-chicago-summit-nato-capabilities.

White House Office of the Press Secretary. 2009. "Fact Sheet on U.S. Missile Defense Policy - A "Phased, Adaptive Approach" for Missile Defense in Europe." *White House.* http://www.whitehouse.gov/the_press_office/FACT-SHEET-U.S.-Missile-Defense-Policy-A-Phased-Adaptive-Approach-for-Missile-Defense-in-Europe.

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